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QUELS DEFIS ? QUELS MODELES POUR Y REPONDRE ? APPLICATION D'UN MODELE ECONOMIE-ENVIRONNEMENT-IMPACTS A L'EVALUATION DES IMPACTS ENVIRONNEMENTAUX EN CHINE INDUITS PAR L'EUROPE, ET AUX TAXES CARBONES AUX FRONTIERES DE L'UE

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Glossaire

ALD: Actual Land Demand
CCF: Company Carbon Footprint
CEE-ONU: Commission Economique pour l'Europe
CH4: Méthane
CO: Monoxyde de carbone
CO2: Dioxyde de carbon
DALY: Disability-Adjusted Life Years
DPSIR: Driving-force, Pressure, State, Impact, Response
EAM: Environmental Accounting Method
EE-IOA: Environmentally Extended Input-Output Analysis
EEA: European Environmental Agency
EF: Ecological Footprint
EIPOT: Environmental Impact of Trade
ELCD: European reference Life Cycle Data system
EMEP: European Monitoring and Evaluation Programme
EPA: U.S. Environmental Protection Agency
EPER: European Pollutant Emission Register
ESA: European System of Accounts
EW-MFA: Economy Wide Material Flow Accounting
GAINS: Greenhouse gas and Air Pollution Interactions and Synergies
GDP: Gross Domestic Product
GHG: Greenhouse gases
GIAN: Geneva International Academic Network
GTAP: Global Trade Analysis Project
HANPP: Human Appropriation of Net Primary Production
IFAC: International Federation of Accountants
IIOA: International Input-Output Association
IMEA: Import Environmental Accounting
INFORUM: INterindustry FORecasting project at the University of Maryland
IO: Input-Output
IOA: Input-Output Analysis
IPCC: Intergovernmental Panel on Climate Change
ISO: Organisation internationale de normalisation
LCA: Life Cycle Assessment
LCI: Life Cycle Inventory
LCIA: Life Cycle Impact Assessment
LRTAP: Convention on Long-Range Transboundary Air Pollution
MFA: Material Flow Accounting
MIPS: Material Inputs Per Service Unit
MRIO: Multi-Regional Input-Output Model
NAMEA: National Accounting Matrix including Environmental Accounts
NMVOC: Composés organiques volatiles non méthaniques

NOX: Oxydes d’azote
OCDE: Organisation de cooperation et de développement économiques
OECD: Organisation for Economic Co-operation and Development
PIOT: Physical Input-Output Tables
PIP: Politique Intégrée des Produits
PM2.5: Particules fines
SAM: Social Accounting Matrix
SEEA: Integrated Environmental and Economic Accounting
SNA: System of National Accounts
SOX: Dioxyde de souffre
TREI-C: Tracking Environmental Impacts of Consumption
UN: United Nations
UNFCCC: United Nations Framework Convention on Climate Change
WF: Water Footprint

Chapitre 1 : I` troductio`

1.1 Co` texte

L'intégration des questions environnementales au sein des processus décisionnels est actuellement à l'ordre du jour des acteurs politiques, des acteurs du tissu économique et des consommateurs. Cette volonté d'intégration fait suite à un long processus de compréhension des relations entre l'homme et son environnement notamment avec la prise de conscience du réchauffement climatique, de son origine anthropique et de l'ampleur potentielle des dégâts économiques (Stern, 2007), sociaux et écologiques (Intergovernmental Panel on Climate Change, 2007; Munn, 2002) qui lui sont liés. La manière d'appréhender la problématique environnementale a ainsi évolué depuis les premières alertes de Rachel Carson (Carson, 1962), et une importance croissante est accordée aux différents aspects environnementaux (EEA, 2005b) ainsi qu'aux chaînes de causalité et des responsabilités qui en découlent.

Les politiques environnementales européennes reflètent cette mutation des perceptions. De la mise en place de solutions de contrôle « end-of-pipe », destinées au traitement de la pollution par ses émetteurs et par les collectivités publiques dans les années 1950 et 1960, elles sont passées à une vision préventive, par l'application de solutions de type « cleaner production » (Ayres & Ayres, 2001) durant les années 1980 ainsi qu'à une vision intégrée considérant les émissions directes et indirectes liées à la fabrication d'un produit et son utilisation, comme par exemple dans la politique intégrée des produits (PIP) au niveau européen. La responsabilité des producteurs est ainsi étendue à la fin de vie de leurs produits et le rôle clé des consommateurs est reconnu (Ernst & Young, 2000). Les solutions sont progressivement envisagées de manière concertée le long d'une chaîne de production-consommation afin d'éviter le déplacement des impacts au sein de celle-ci, par exemple, par substitution de produits, matière, énergie ou technologies. La nécessité d'une vision multicritères s'est également imposée. Tant les problématiques classiques comme les pollutions de l'air, de l'eau et du sol que les problématiques nouvelles comme la potentielle dématérialisation de l'économie européenne suite à son évolution structurelle vers la tertiarisation sont actuellement considérées. Cette vision se manifeste par l'utilisation de jeux d'indicateurs environnementaux intégrant pollution de l'air, de l'eau et des sols par l'Agence Environnementale Européenne (EEA, 2005a), ou encore par l'extension des comptes nationaux européens avec des comptes satellites (United Nations *et al.*, 2003), intégrant les émissions et l'utilisation des ressources au niveau national.

1.1.1 Développeme` t des méthodes d'évaluatio` des impacts de l'homme sur so` e` viro` ` eme` t

Ces nouvelles perceptions et problématiques ont conduit à l'évolution des méthodes d'évaluation des impacts (dans leur sens commun) de l'homme sur son environnement selon deux axes significatifs qui permettent d'en comprendre les enjeux actuels.

Le premier axe est l'émergence et la croissance rapide d'une perspective quantifiée et intégrée de type cycle de vie (life cycle thinking, en anglais). Cette perspective est définie par le Centre Commun de Recherches de la Commission Européenne comme ayant pour objectif de permettre des prises de décision, dans les politiques publiques et par le secteur privé, en considérant les effets environnementaux tout au long des chaînes de production, l'utilisation et la fin de vie des produits (European Comission, 2003). L'importance croissante de cette perspective est actuellement manifeste au sein de la législation européenne et des normes d'application volontaire, tel que le montre l'extension actuelle du protocole GHG par la prise en compte des émissions en amont et en aval des sites de production, dénommées « scope 3 » (WRI & WBCSD, 2009). Cette perspective est un changement conceptuel ayant de nombreuses conséquences pratiques comme, par exemple, la difficulté à calculer des indicateurs, compte-tenu de la quantité importante d'informations à collecter et structurer sur toute une chaîne de production-consommation. Une autre difficulté est liée à la comparaison de ces indicateurs ayant une perspective cycle de vie avec les indicateurs socio-économiques existants, qui, eux, ne l'appliquent pas. A titre d'exemple, cette perspective implique au niveau national un calcul pour une consommation donnée et non pas un calcul se référant à un territoire ou à un critère d'appartenance nationale, tels que ceux fournis par les comptes nationaux ou résultants du protocole de Kyoto par exemple (Peters, 2008). Les perspectives dites consommateurs (consumer-oriented, en anglais) sont donc largement différentes des perspectives dites producteur (producer-oriented, en anglais).

Le deuxième axe est le développement de multiples approches permettant de délivrer des indicateurs synthétiques afin de permettre une prise de décision. Cette réduction de la complexité est nécessaire suite au grand nombre de flux environnementaux considérés et mesurés à différents niveaux. Ces flux sont liés aux différentes fonctions de la nature en tant que facteur de production (ressources), assimilateur des déchets de la société (polluants) et source de bien-être matériel (par exemple le calme) (Burgenmeier *et al.*, 2007). L'empreinte écologique agrège ainsi en un indicateur unique « la demande de l'humanité en espace produisant des ressources et en espace séquestrant les émissions de carbone d'origine fossile » (Piguet *et al.*, 2007). Le cadre conceptuel DPSIR (Driving-forces, Pressure, State, Impact, Response) est une des représentations utilisées par l'Agence

Environnementale Européenne et l'OCDE pour représenter ces différents niveaux de mesure : les forces humaines sous-jacentes, les pressions sur l'environnement, l'état de l'environnement, les impacts et les réponses de la société (EEA, 1997; Kristensen, 2004).

Ces nouvelles conceptions de la politique environnementale ont ainsi pour conséquence un besoin accru en information environnementale quantifiée, en concepts et en outils d'analyse. Ces besoins vont au-delà de ce qu'apportent les collections d'émissions que sont les inventaires, tels que CORINAIR (EEA, 2007) ou le registre européen des rejets et transferts de polluants (EPER) au niveau européen. Reflétant les émissions directes d'activités socio-économiques, ces inventaires ne proposent pas de vision de type cycle de vie. Constitués, par nature, d'une collection de flux hétérogènes, ils n'offrent pas non plus de vue synthétique. C'est à ces besoins méthodologiques et pratiques que répondent, ce que nous nommons les méthodes de comptabilité environnementale. La comptabilité environnementale est donc un sujet d'intérêt croissant, aux enjeux économiques, politiques et environnementaux actuels.

Nous définissons les méthodes de comptabilité environnementale comme toute méthode permettant la quantification, la synthèse et l'analyse des impacts environnementaux (dans leur appellation commune) selon une vision cycle de vie afin de permettre une prise de décision et communiquer au sujet de ces impacts. Ces méthodes sont appelées en anglais « environmental accounting methods » et nous utiliserons leur acronyme EAM dans la suite du texte. Les grandes familles d'EAM sont l'analyse du cycle de vie (life cycle assessment, en anglais ou LCA) (Jolliet *et al.*, 2005), l'analyse entrées-sorties étendue (input-output analysis, en anglais ou IOA) (Suh, 2009), l'analyse de flux de matière (material flow accounting, en anglais ou MFA) (OECD, 2008; Weisz *et al.*, 2007), et les empreintes environnementales dont la plus connue est l'empreinte écologique (ecological footprint, en anglais ou EF) (Wackernagel *et al.*, 2002).

Nous qualifions la période actuelle de période de convergence au regard de la situation des EAMs. Tout d'abord, convergence entre le monde scientifique et le monde politique. L'intérêt nouveau porté par l'ensemble des acteurs de la société pour ce type d'approche mène à une consolidation des efforts de collecte, comme par exemple la plateforme européenne sur l'analyse de cycle de vie et le développement de la base de données de référence européenne (ELCD) (European Comission & JRC), et de validation des données ainsi qu'à une réflexion sur l'utilisation effective des indicateurs. De nombreux rapports sont commandés par les instances politiques de l'UE ou des pays européens pour évaluer le positionnement des indicateurs fournis par les EAMs, par exemple l'empreinte environnementale, par rapport aux indicateurs existants et leur potentiel d'application (Best *et al.*, 2008). Bien que n'ayant pas encore atteint leur phase de maturité, l'utilisation de ces EAM est préconisée par différentes lois et normes d'application volontaire. Les comptes satellites des comptes nationaux depuis 1993 sont ainsi complétés depuis 2005 par des recommandations sur la mise en place d'une comptabilité environnementale au niveau des entreprises, par la Fédération Internationale des Comptables IFAC (Jasch & Savage, 2005). Au niveau des produits, plusieurs normes sont actuellement en cours d'élaboration par l'ISO, ou l'AFNOR (en France) ainsi que par la British Standards Institution comme la PAS 2050:2008 sur les gaz à effet de serre liés aux biens et services (BSI, 2008). La convergence est également perceptible entre les communautés scientifiques qui s'engagent dans un processus de comparaison des méthodes et des indicateurs. Il en résulte des combinaisons de méthodes appelées hybridation, et l'inclusion d'approches provenant d'autres disciplines comme l'économie ou la sociologie. Cette période a commencé il y a peu, et des recherches sont encore à effectuer pour permettre un dépassement des limites théoriques et pratiques des EAM actuelles. Les objectifs sont multiples, allant de la livraison d'indicateurs quantifiés des impacts environnementaux qui soient auditables, au développement et à la réalisation d'un cadre comptable cohérent à de multiples échelles afin de compléter la comptabilité nationale et la comptabilité des entreprises.

1.1.2 Nouveaux défis liés à la mo` dialisatio`

Les EAMs font actuellement face à de nouveaux défis liés à la mondialisation économique. Celle-ci est caractérisée par la taille sans précédent des échanges internationaux (commerce de biens et services et flux de capitaux) et des phénomènes de délocalisation (offshoring, en anglais) et de réorganisation (outsourcing, en anglais) des activités économiques (Abonyi, 2006). Bien que certains liens commerciaux entre pays soient bâtis sur des notions de spécialisation, la plupart des échanges internationaux sont constitués de biens similaires dont la part des biens intermédiaires (commerce entre entreprises) est en augmentation (Bernard *et al.*, 2007). Il en résulte un éclatement spatial des chaînes de production-consommation à travers le monde. Cette fragmentation spatiale des processus physiques de production est complétée par une large distribution spatiale des propriétaires du facteur de production capital (les infrastructures nécessaires à la production). Par exemple, une compagnie française, partiellement propriété de fonds de pension américains, produit des composants électroniques en Chine dans une usine partiellement propriété du gouvernement chinois, qui seront incorporés au Japon dans une télévision de marque japonaise, vendue à des consommateurs allemands.

Cette distance croissante entre les propriétaires des moyens de productions, les producteurs, les consommateurs et ceux qui subissent les impacts environnementaux découlant des activités de production et de consommation, complique la tâche des méthodes de comptabilité environnementale. Parmi les difficultés rencontrées par les EAMs mentionnées dans la littérature, trois nous semblent représentatives de l'ampleur des défis que pose la mondialisation : 1) l'attribution des responsabilités pour ces impacts (Lenzen *et al.*, 2007), 2) l'importance croissante de nouvelles problématiques environnementales peu considérées dans les EAMs jusqu'à présent et la prise d'importance de problématiques secondaires en Europe mais essentielles dans les pays des nouveaux partenaires commerciaux (qualité et la quantité d'eau, impacts sur la santé humaine) (Ministry of Environmental Protection. The people's Republic of China, 2009), ainsi que 3) le besoin de modéliser les impacts environnementaux des produits importés selon une perspective cycle de vie (Turner *et al.*, 2007).

En terme de modélisation, la quantification et la localisation des impacts environnementaux liés aux importations sont complexes pour diverses raisons. La littérature scientifique recense plusieurs facteurs expliquant cette complexité. Cinq d'entre eux, sont donnés ici à titre d'exemple, et choisis en raison de leurs liens avec ce travail de thèse. Les deux premiers facteurs sont le manque de données et le manque de modèles pour modéliser les activités de production et leurs émissions selon une perspective cycle de vie. Les bases de données globales, tant économiques qu'environnementales, sont rares et peu détaillées tandis que les bases de données détaillées sont limitées aux pays développés. Parmi les modèles dits « d'obédience physique », c'est-à-dire traitant des divers flux ayant une existence physique (matières, polluants, énergie, …), seuls des modèles de type LCA et MIPS (material input per service unit, en anglais) (Ritthoff *et al.*, 2002) permettent une modélisation du cycle de vie. Cependant, leur application à large échelle, pour obtenir une vision au niveau national par exemple, est peu réaliste car ils demandent de modéliser un nombre important de produits différents. Parmi les modèles dits « d'obédience économique », susceptibles de fournir une vision agrégée, seuls les modèles entrées-sorties en sont capables. Ils ne considèrent cependant que les phases liées à la production mais pas celles liées à l'utilisation ni la fin de vie des produits. Les autres modèles existants, par exemple les modèles d'équilibre général néo-classiques (Vargas, 1999) ou les modèles multi-sectoriels économétriques de type INFORUM (Almond, 2003; Guillet, 2003), ne permettent pas de considérer les impacts au niveau des chaînes de production dans leur dimension internationale.

Les deux facteurs suivants concernent l'évaluation des importations et sont liés à la difficulté de modéliser les échanges. Bien que le commerce international soit un des aspects économiques les plus surveillés, et donc quantifié, pour des raisons historiques (taxes douanières d'importation et d'exportation), les données du commerce international manquent de cohérence (Gou *et al.*, 2009). Les données sur le commerce entre pays de l'EU ne sont, de plus, plus collectées depuis la disparition des frontières intérieures et les modèles théoriques et appliqués (comme les modèles de gravité), du commerce international sont encore peu appliqués, à l'exception de (Duchin, 2005), car peu capables de représenter les flux constatés dans la réalité. Le transport international est également difficile à considérer puisque tant la quantité et la localisation des différentes émissions que le lien entre les modes de transports et les contenus transportés sont peu documentés, rendant difficile leur calcul et leur affectation à des chaînes de production. Un type d'échange additionnel doit, de plus, être également considéré dans une perspective globale : les échanges de polluants à travers les medias environnementaux (air, eau et sol) afin de permettre l'identification des pays dans lesquels ont lieu les impacts. Les modèles de transport atmosphérique comme EMEP en Europe, ont, en effet, démontré qu'une importante partie des polluants émis dans un pays est déposée dans un pays tiers (EMEP, 2005). Bien que de nombreux modèles atmosphériques existent, les modèles adaptés aux besoins des EAMs sont cependant encore rares à l'échelle mondiale. L'évaluation des impacts liés aux importations, comme des autres biens, demande donc de combiner différents types de modèles permettant de considérer les émissions liées aux étapes de production, de consommation et d'échanges de biens et services ainsi que des modèles atmosphériques modélisant les échange de polluants.

Le dernier facteur est lié à la contradiction inhérente à la poursuite actuellement simultanée de deux objectifs : une couverture des impacts à l'échelle mondiale et une précision des résultats attendue au niveau d'un pays ou d'un produit. Une couverture mondiale implique une démarche basée sur des modèles mondiaux caractérisés par la simplification de nombreux paramètres et l'imputation de valeurs manquantes à partir de données génériques : la cohérence globale est privilégiée au détriment des détails. La précision des résultats demande au contraire, une approche régionale, voire locale, plus minutieuse. Cette contradiction demande à être résolue afin d'atteindre ces deux objectifs.

Ces différents facteurs sont, avec d'autres, une des raisons pour lesquelles la mondialisation est un défi sérieux auquel les EAMs sont, depuis peu, confrontées. Y faire face demande, à notre avis, d'aller au-delà de l'extension mécanique des méthodes d'évaluation actuelles par la prise en compte des impacts liés aux importations, même si celle-ci est, bien entendu, nécessaire. Nous estimons qu'une réponse à ce défi réside dans le traitement des questions de fond, comme par exemple, celle de savoir s'il est possible, et même souhaitable, de chercher à atteindre une vision mondiale avec chacune des EAMs existantes, compte-tenu des difficultés méthodologiques et en terme de données, ainsi que de la diversité des profils régionaux.

1.2 Objectifs

Cette thèse traite de l'intégration des contraintes liées à la mondialisation, des échanges et des responsabilités, au sein des méthodes de comptabilité environnementale destinées à quantifier les impacts environnementaux des biens, services, entreprises, individus et nations. Notre premier objectif est d'établir un cadre d'analyse permettant l'évaluation des forces et faiblesses des EAMs existantes ainsi que de leur potentiel d'intégration des problématiques liées à la mondialisation. Notre deuxième objectif est d'analyser les principales EAMs à l'aide de ce cadre d'analyse. Notre troisième objectif est de faire un pas en direction de l'intégration des contraintes liées à la mondialisation en étendant une EAM existante, choisie à l'aide du cadre d'analyse. Notre quatrième objectif est d'appliquer ce nouveau modèle pour étudier trois problèmes clés liés à la mondialisation et confirmer ainsi l'apport de l'approche proposée. Ces trois problèmes sont les impacts environnementaux sur la santé humaine dans les pays en voie de développement, les tarifs douaniers aux frontières de l'Europe liés au contenu en carbone des produits importés et le rôle des pays développés dans les émissions de carbone chinoises.

1.3 Démarche

1.3.1 Diag` ostic et a` alyse des EAMs

Le développement d'un cadre d'analyse des EAMs est le premier objectif de cette thèse. Ce cadre d'analyse a été développé dans le cadre du projet européen IMEA (Imports Environmental Accounting) (Blanc *et al.*, 2009). Divers cadres analytiques sont disponibles, mais ils ne correspondent pas aux besoins d'évaluation actuels des EAMs tels que nous les avons définis dans l'introduction. Il manque ainsi un cadre d'analyse qui leur soit spécifique et fasse ressortir ce qu'elles ont en commun et leurs différences, les attentes de la société envers ces méthodes ainsi que les défis posés par la mondialisation auxquels elles doivent faire face. Certains cadres d'analyse sont focalisés sur des points méthodologiques précis tels que l'évaluation de la qualité des données (Weidema, 1998). D'autres cadres d'analyse sont très généraux et s'appliquent à tous types de méthodologie de développement d'indicateurs tel le cadre européen dénommé RACER (relevant, accepted, credible, easy, and robust, en anglais) (European Commission, 2005). Les deux projets d'évaluation d'EAM récents ont ainsi présenté leur version du RACER. Il s'agit d'une évaluation de l'empreinte écologique nommée « Potential of the ecological footprint for monitoring environmental impacts from natural resource use: Analysis of the potential of the ecological footprint and related assessment tools for use in the EU's thematic strategy on the sustainable use of natural resource » (Best *et al.*, 2008) et du projet EIPOT (Lutter & Giljum, 2008) en 2008.

La démarche retenue, permettant la définition d'un cadre analytique apte à traiter les EAMs et les nouveaux enjeux liés à la mondialisation, a été de développer un premier jeu de questions, inspiré des cadres existants, et de le compléter par les éléments *ad-hoc* qui ressortaient des discussions avec des spécialistes des EAMs et de la comptabilité environnementale. Ce questionnaire a été soumis aux partenaires du projet IMEA afin d'obtenir une description, aussi exhaustive que possible, des différentes EAMs. L'analyse de leurs réponses et de la littérature scientifique a permis l'identification des éléments communs aux EAMs et de leurs différences - dans ce qu'elles sont et comment elles fonctionnent - ainsi que des attentes et défis auxquels elles doivent répondre. Ces éléments identifiés ont été discutés dans un atelier organisé dans le cadre du projet IMEA, regroupant partenaires et parties prenantes, telles que les offices statistiques, les groupes de recherche, les membres de diverses organisations et des membres des instances européennes.

Nous proposons ici un cadre de réflexion visant à combler un manque pour permettre une analyse, détaillée et reproductible, d'une méthode de comptabilité environnementale, ainsi qu'une vision synthétique permettant la comparaison entre méthodes. Ce cadre utilise un vocabulaire acceptable par les spécialistes des différentes méthodes. Il tire profit des cadres d'analyse existants et les étend aux questions spécifiques à la mondialisation, qui ne sont pas encore traitées. Il mentionne explicitement les caractéristiques-clés attendues des EAMs - ce qu'elles sont et comment elles fonctionnent - ainsi que les attentes sociétales à leur égard et les défis liés à l'intégration des questions internationales et transfrontalières. Ce cadre analytique est un premier pas. Il fournit une première structure cohérente de réflexion sur les EAMs, qui peut servir de base de discussion pour la détermination d'un cadre standardisé commun destiné à l'évaluation des nouvelles EAMs et des modifications apportées aux EAMs actuelles.

L'analyse des EAMs existantes est notre deuxième objectif. Seize EAMs ont été analysées à l'aide du cadre d'analyse développé précédemment. Nous avons analysé les méthodes LCA et IOA ainsi que les méthodes hybrides, et avons effectué la synthèse générale des autres méthodes analysées par nos partenaires. En exploitant ces résultats, nous avons qualifié la satisfaction de la réponse apportées par les EAMs aux attentes sociétales et défis liés à la mondialisation ; nous avons également identifié la ou les méthode(s) prometteuses(s) pour traiter les contraintes liées à la mondialisation de manière adéquate ainsi que ses (leurs) manques actuels. Des pistes de développement futur ont également été proposées.

Les résultats de cette analyse corroborent les résultats récemment publiés sur le même sujet par le projet EIPOT, tout en leur apportant un éclairage plus méthodologique grâce au cadre d'analyse mentionné. Les résultats de cette deuxième partie de thèse font particulièrement ressortir qu'un élément clé de la modélisation des importations est la capacité à fournir une perspective cycle de vie à l'échelle mondiale. Cette capacité d'allocation globale, telle que nous la nommons, n'est possible qu'avec quatre EAMs : IOA, PIOT (tables entrées-sorties physiques ou « physical input-output tables », en anglais) (Giljum & Hubacek, 2008; Helga Weisz & Duchin, 2006), MIPS et LCA. La méthode IOA semble être la plus adaptée des quatre pour modéliser les phases de production : les approches PIOT et MIPS sont très peu utilisées et les données rares, tandis que l'approche LCA est peu adaptée à son déploiement systématique à l'échelle mondiale. Nous avons, par conséquent, décidé d'étendre un modèle IOA existant dans la troisième partie de cette thèse.

1.3.2 Modèle i` tégré Eco` omie-E` viro` ` eme` t-Impacts

L'intégration des contraintes liées à la mondialisation dans un modèle quantifié est notre troisième objectif.

Le développement des modèles entrées-sorties, mono-pays et étendus avec des émissions, est actuellement bien répandu en Europe; les tableaux entrées-sorties sont fournis de manière standardisée par Eurostat tant pour la partie économique que pour certaines extensions environnementales (Eurostat, 2001). Il existe également des modèles interrégionaux, tels que celui décrit par (Miller & Blair, 1985) et appliqués dans plusieurs pays, dont la Belgique (Avonds, 2008) ou la Chine (Ichimura & Wang, 2003), qui peuvent être exploités au niveau international moyennant quelques adaptations. Il est par conséquent possible, en se basant sur ces modèles, de développer des modèles dits multi-régions (MRIO : « multi-regional input-output model » en anglais) à l'échelle mondiale (Peters & Hertwich, 2007; Thomas Wiedmann *et al.*, 2007).

Ce type de modèle intègre de manière explicite le commerce international entre les différents pays, ou régions, et les échanges commerciaux entre les secteurs économiques au sein de chaque économie. Les modèles MRIO permettent ainsi d'obtenir une vision cycle de vie à l'échelle mondiale par la modélisation des chaines de production-consommation. Cette vision mondiale est obtenue au détriment de la précision des résultats et des détails de l'analyse. Ce compromis nous a cependant paru scientifiquement valable dans une phase où il s'agit d'explorer et de montrer la pertinence ou non, de l'approche suivie et pour laquelle des ordres de grandeurs sont une réponse suffisante. Ce choix est indirectement validé par l'Union Européenne qui finance un projet du même type, mais à plus vaste échelle puisqu'intégrant une trentaine de partenaires, dénommé EXIOPOL (Tukker *et al.*, 2006). Une seule base de données contenant des informations sur les tableaux entrées-sorties au niveau mondial étant disponible actuellement (GTAP) (Dimaranan, 2006), nous avons choisi de l'utiliser et de l'adapter à nos besoins, malgré ses faiblesses reconnues, comme par exemple l'extension et l'harmonisation des tableaux entrées-sorties avec leurs propres méthodes, non validées scientifiquement. Cette approche est également adoptée par les autres scientifiques travaillant dans ce domaine émergent comme Peters and Hertwich (2006) ou Nijdam and Wilting (2003).

Ce modèle économique mondial a été étendu avec les émissions suivantes : dioxyde de carbone (CO_2) (source : GTAP), méthane (CH_4), monoxyde de carbone (CO), composés organiques volatiles non méthaniques (NMVOC), oxydes d'azote (NO_x), et dioxyde de soufre (SO_x) provenant de la base de donnée EDGAR (van Aardenne *et al.*, 2005) adaptée à notre modèle. Un inventaire mondial des émissions de particules fines ($PM_{2.5}$) a également été développé spécifiquement pour ce travail, aucun n'étant disponible. Cet inventaire se base sur les données existantes au niveau européen (inventaire LRTAP (EEA, 2009), modèle RAINS (Klimont *et al.*)), les comptes satellites NAMEA (Eurostat, 2001; Keuning *et al.*, 1999), les répertoires d'émissions américain, canadien et mexicain (Instituto Nacional de Ecología *et al.*, 2006) (le seul disponible pour un pays en voie de développement lors de la réalisation de cet inventaire) ainsi que sur un inventaire pour l'Asie (CGRER, 2006) et des études spécifiques à certains pays comme le Japon ou spécifiques à une source d'émission comme les transports. Ce modèle multi-régional entrées-sorties étendu (« environmentally extended MRIO », en anglais) permet donc de quantifier les pressions liées à ces polluants lors des phases de production (« Pressures » dans le DPSIR) au niveau mondial.

Afin de permettre une quantification au niveau des impacts (« Impacts » dans le DPSIR), ce modèle économique étendu a été couplé à un modèle multi-continental, multi-media (air-eau-sol) de transport de polluants et d'exposition humaine ainsi qu'à des facteurs de dommages sur la santé humaine. Ce modèle intégré économie-environnement-impacts permet ainsi de quantifier les impacts environnementaux sur la santé humaine liés aux émissions de particules fines. Ce polluant a été choisi comme polluant représentatif puisqu'il est un des contributeurs majeurs des impacts environnementaux sur la santé humaine (Humbert *et al.*, 2009). Le modèle de transport, dont seule la partie atmosphérique est valorisée ici, est nommé « IMPACT World » et est développé à l'Université du Michigan (Jolliet, 2009). Les facteurs de dommages proviennent du modèle IMPACT02+ (Jolliet *et al.*, 2003). « IMPACT World » permet également de quantifier l'exposition humaine à d'autres polluants. Celle-ci sera possible lorsque des bases de données d'émissions par secteur auront été élaborées au niveau mondial. Le choix de ce modèle et des facteurs de dommages a été dicté par deux considérations. Tout d'abord, la nécessité de travailler en équipe multidisciplinaire dans un projet demandant des compétences multiples comme celui-ci, et la possibilité de collaborer avec les développeurs de la méthode de référence en Europe concernant la diffusion des polluants et le calcul des impacts sur la santé humaine. Ensuite, la possibilité d'un développement concomitant des deux parties du modèle (économique et environnement) permettant une meilleure compréhension des possibilités et des limites d'un tel couplage. D'autres modèles de diffusion atmosphériques, complétés par des données de population, pourraient être sélectionnés dans le futur pour compléter le modèle économique. Il nous semble cependant que l'aspect le plus pertinent serait de coupler le modèle économie-environnement à d'autres facteurs de dommages. Ceux utilisés dans le modèle actuellement ne sont, en effet, pas propres à chaque région mais calculés pour l'Europe (Jolliet *et al.*, 2003). De tels facteurs de dommage régionalisés ne sont cependant pas encore développés.

La spécificité du modèle économie-environnement-impacts développé est d'intégrer la production, la consommation et les échanges de biens et de particules fines ($PM_{2.5}$) au niveau mondial afin de quantifier et de localiser les impacts sur la santé humaine liés à ces particules selon une perspective cycle de vie mondiale. Ce travail étend la première version développée par la même équipe, avant le début de cette thèse, dans le projet TREI-C (« Tracking Environmental Impacts of Consumption » partiellement financé par le GIAN (RUIG GIAN).

Les modèles MRIO mondiaux sont des modèles permettant le calcul d'un grand nombre d'indicateurs, caractérisant des régions, des produits ou des chaines de production. La lecture de leurs résultats est cependant malaisée et leur potentiel analytique est par conséquent encore sous-exploité. Nous avons donc proposé une clé de lecture des résultats en appliquant une agrégation sectorielle afin d'obtenir une vision des relations entre pays uniquement. Nous avons également proposé une exploitation d'une des spécificités de ces modèles à des fins analytiques.

Bien que le potentiel analytique des modèles entrées-sorties ait été exploré dans de nombreux articles, publiés principalement dans le journal « Economic Systems Research », comme par exemple (Fernandez-Vazquez *et al.*, 2008), le potentiel spécifique des modèles MRIO est cependant encore sous-exploité. Leur principale différence par rapport à un modèle national étant de rendre endogène le commerce international (exportations et importations), nous avons exploité cette propriété pour développer un nouveau type d'analyse que nous avons appelé « décomposition en flux sous-jacents » ou « underlying-flows decomposition » en anglais afin de permettre de nouvelles capacités analytiques spécifiques au niveau international. La démarche suivie fut tout d'abord d'essayer de répondre à un problème qui s'est concrètement posé : l'identification des pays/régions du modèle qui induisent les flux économiques et les émissions dans une région considérée, selon une perspective cycle de vie. La solution analytique nécessaire pour répondre à cette question étant encore inexistante, du moins à notre connaissance, nous l'avons développée pour permettre une compréhension plus approfondie du phénomène étudié. Le potentiel analytique additionnel fourni par cette réponse a ensuite été exploré.

Les cinq contraintes liées à la mondialisation intégrées au cours de la modélisation sont les suivantes :

- l'extension d'un modèle de cycle de vie national (de type entrées-sorties) au niveau mondial ;
- l'extension de ce modèle avec sept polluants dont les particules fines, avec une base de données mondiale développée à cet objet ;
- le couplage de ce modèle étendu avec un modèle de dispersion atmosphérique mondial ;
- le couplage de ces deux modèles avec un modèle permettant l'évaluation des dommages liés aux particules fines en termes d'impact sur la santé humaine ;
- le développement de nouvelles capacités analytiques spécifiques à l'aspect international du modèle proposé.

1.3.3 Applicatio` s du modèle Eco` omie-E` viro` ` eme` t-Impacts

L'évaluation de l'apport des approches proposées est le quatrième objectif de cette thèse. Cette évaluation s'effectue en fournissant une réponse quantifiée à trois questions et en déterminant si l'intégration des contraintes liées à la mondialisation est un élément essentiel de la réponse. L'intérêt de cette estimation quantitative est de corroborer ou d'infirmer les résultats de l'analyse des EAMs qui fournit la justification conceptuelle au développement d'un tel modèle. Trois questions sont ainsi explorées en deux applications :

1. Quelles sont la magnitude, et la localisation, des impacts sur la santé humaine induits par la consommation des pays développés dans les pays en voie de développement, par le biais de la production de leurs exportations et compte-tenu des chaînes de production-consommation mondiales ?

2. Un tarif douanier approximant le contenu attaché[1] en carbone des importations aux frontières de l'Europe en se basant sur le pays d'origine est-il réalisable et quelle est sa pertinence en terme de couverture du total des émissions ?

[1] Le contenu attaché en carbone (« embodied carbon content » en anglais) représente les émissions de carbone ayant eu lieu le long de la chaine de production d'un bien (Wyckoff & Roop, 1994).

3. Dans le cadre d'un partage des coûts de dé-carbonisation de pays tels que la Chine par les pays développés, quel pourrait être un schéma de partage basé sur les émissions induites par chacun des pays en Chine ?

Différents modèles, variant en nombre de régions et de secteurs, ont été développés pour répondre à ces questions. Le modèle principal décrit la production (24 secteurs), la consommation et les échanges internationaux de biens, services et polluants par les acteurs majeurs (actuels et futurs) de l'économie internationale que sont les Etats-Unis, l'Allemagne, l'Europe, la Chine, et l'Inde ainsi que quatorze autres régions, couvrant le monde et déterminées selon la classification des Nations-Unies (United Nations), ainsi que pour un secteur de transport supra-national.

Nous avons validé nos résultats de manière externe, d'une part par comparaison avec des résultats publiés s'il en existe, et d'autre part par discussion avec les spécialistes développant des modèles similaires. Pour les résultats en terme de santé humaine, nous avons effectué une évaluation quantitative des incertitudes. Cette évaluation des incertitudes a été faite en faisant varier tous les paramètres du modèle et en identifiant les conséquences de ces variations sur les principaux résultats. Cette analyse nous a permis d'identifier les paramètres clés du modèle et de vérifier si les résultats restaient cohérents malgré les changements. Cette approche va au-delà ce que qui est généralement effectué dans le domaine puisque Wiedmann *et al.* (2008) mentionnent l'inexistence de ce type d'analyse sur les modèles MRIO.

Le modèle a tout d'abord permis de quantifier les impacts sur la santé humaine induits par la consommation de l'ensemble des régions du modèle et d'en analyser les causes physiques ou socio-économiques principales. Nous en avons également tiré les conséquences afin de répondre à une question de fond liée à la problématique commerce-environnement. La question de fond traitée est de savoir si le commerce international tend à favoriser la délocalisation des productions les plus dommageables du point de vue de l'environnement. Cette question a déjà reçu de nombreuses réponses tant de la part d'économistes (Anriquez, 2002; Copeland & Taylor, 2003), que de spécialistes des EAMs dont celle de Dietzenbacher et Mukhopadhyay (2007) qui ont appliqué un modèle entrées-sorties à l'Inde. Notre réponse innove sur cette question en considérant explicitement les dommages sur la santé humaine et en prenant explicitement en compte les chaînes de production-consommation au niveau mondial.

Le modèle a ensuite permis de quantifier les émissions de carbone induites par la consommation de l'ensemble des régions du modèle. Nous avons appliqué à ce modèle les outils analytiques développés afin de répondre aux questions deux et trois. La question des tarifs douaniers est approchée selon deux manières complémentaires. La clé de lecture mentionnée précédemment est tout d'abord appliquée aux importations allemandes de biens finaux afin de déterminer la pertinence d'un tarif carbone basé sur la région d'origine des biens importés, tel que cela a été proposé aux membres de l'EU par le Président de la République Française (Faujas, 2009). Cette pertinence est établie en déterminant la part du carbone qui provient effectivement de la région d'origine des biens finaux importés par l'Allemagne. La « décomposition en flux sous-jacents » est ensuite appliquée, en tant qu'exemple, à la Chine afin de déterminer la part des émissions chinoises qui échapperait à un tel système. Ces émissions sont celles découlant de son rôle de fournisseur de biens intermédiaires, dans les chaines de production mondiales, à un partenaire commercial non européen qui utilisera ce bien pour produire un bien final qui sera consommé en Europe. La troisième question, le schéma de partage des coûts de dé-carbonisation, est également traitée à l'aide de cette « décomposition en flux sous-jacents ». Cette décomposition permet de déterminer quelle pourrait être la clé d'allocation des coûts de dé-carbonisation de la Chine qui pourrait être mise sur pied en se basant sur le postulat que ces coûts sont proportionnels à la contribution des pays étrangers dans les émissions chinoises. L'approche développée permet de déterminer cette contribution selon une optique consommation: chacune des émissions chinoises est attribuée à une chaîne de production-consommation dont le bénéficiaire final (un consommateur) est identifié et localisé. L'ensemble des émissions peut ainsi être alloué aux différents pays. L'approche proposée se base sur une logique de causalité. D'autres optiques pourraient également être appliquées, avec d'autres modèles, telle qu'une vision politique ou une vision basée sur les capacités financière des différents pays.

La suite de ce document de thèse s'articule autour de trois chapitres sous forme d'articles en anglais et commençant par une traduction en français de leur introduction, des résultats principaux et des conclusions. Le second chapitre décrit le cadre d'analyse des EAMs ainsi que l'évaluation des principales EAMs. La capacité des EAMs à répondre aux attentes sociétales et aux challenges de la mondialisation y est discutée. Le troisième chapitre décrit le modèle intégré économie-environnement-impacts et son application pour quantifier les impacts environnementaux sur la santé humaine liés aux particules fines au niveau mondial. Le quatrième chapitre décrit la structure du modèle économique ainsi que les outils analytiques (« décomposition en flux sous-jacents ») développés. Ces outils sont appliqués aux questions sur les tarifs douaniers aux frontières de l'Europe liés au contenu en carbone attaché des produits importés et sur le rôle des pays développés dans les émissions de carbone chinoises. Une conclusion est proposée dans le dernier chapitre.

Chapitre 2 : Diagnostic et analyse des EAMs

Ce chapitre s'appuie sur une proposition d'article rédigée en anglais et à soumettre au « Journal of Industrial Ecology » par les auteurs suivants : Damien Friot, Isabelle Blanc et Lucien Wald. Nous proposons tout d'abord un résumé étendu de son contenu, qui sera suivi du texte de l'article *in extenso*.

2.1 Résumé étendu

L'intégration des questions environnementales au sein des processus décisionnels est actuellement à l'ordre du jour des acteurs politiques, de ceux du tissu économique et des consommateurs. Cette intégration s'appuie sur diverses méthodes de comptabilité environnementale, désignées ici sous le nom de EAM selon l'acronyme anglais (environmental accounting method). Chaque EAM a été développée spécifiquement afin de quantifier une, ou plusieurs, facette des impacts de l'homme sur l'environnement. Ces méthodes sont cependant toutes confrontées aux mêmes défis concernant leur capacité d'appréhension de la mondialisation des échanges économiques. Elles sont également confrontées aux mêmes attentes sociétales quant à leurs réponses, dont, en particulier, leur capacité à fournir des indicateurs scientifiquement valides et couvrant adéquatement les diverses préoccupations environnementales.

La mise en place d'un cadre d'analyse, destiné à l'étude des réponses fournies par les EAMs face à ces attentes et défis, ainsi que l'exploration de ces réponses, sont les objectifs de cet article. Nous énumérons tout d'abord neuf attentes et leurs défis. Nous envisageons ensuite de manière synthétique les réponses apportées par les principales EAMs en analysant ce que sont les EAMs et leur fonctionnement. Une grille d'analyse synthétique est enfin proposée afin de permettre une analyse ultérieure des autres EAMs.

Les attentes sociétales envers les EAMs peuvent être envisagées selon trois angles: le développement durable, la comptabilité environnementale et les processus décisionnels. Le développement durable demande une vision cohérente qui passe par la comparabilité, et même l'intégration, des indicateurs économiques, sociaux et environnementaux. Les indicateurs environnementaux provenant des EAMs doivent, par conséquent, considérer explicitement les liens entre les activités humaines et divers types d'impacts environnementaux, selon une perspective de cycle de vie et aux diverses échelles pertinentes. Les besoins relatifs aux impératifs d'une comptabilité sont de fournir des résultats quantifiés et robustes d'un point de vue théorique, des modèles et des données, ainsi que de fournir une capacité analytique permettant l'identification et le suivi des principales causes sous-jacentes des résultats agrégés que sont les indicateurs. Selon l'angle décisionnel, les indicateurs doivent être utilisables, c'est-à-dire correspondre à des critères de pertinence, d'intelligibilité, d'univocité, d'acceptabilité et de facilité de réalisation à un coût considéré comme acceptable.

Les défis liés à la mondialisation affectent ces attentes. L'objectif de comparabilité demande un cadre comptable interrégional qui considère les différents modes de production et de consommation régionaux ainsi que deux types d'échanges entre régions (le commerce international de biens et services et les transferts transfrontaliers de polluants au sein des medias environnementaux (air, eau et sol)) et le transport international. De nouveaux modèles et jeux de données, robustes, doivent ainsi être développés ainsi que de nouvelles capacités analytiques. Ces nouveaux modèles et jeux de données doivent être capables de représenter une perspective de cycle de vie au niveau mondial ainsi que les spécificités régionales des différentes étapes des chaînes de production-consommation. Les aspects liés tant à la mondialisation qu'à la régionalisation sont par conséquent un défi actuel pour les EAMs. La complexité à représenter ces chaînes de production-consommation mondiales remet en question la robustesse des résultats obtenus par les EAMs. Les besoins significatifs en modèles et en données posent également la question de la faisabilité d'une évaluation mondiale, multi-échelles avec chacune des EAMs disponibles. La question de la pertinence de chaque EAM par rapport à un contexte géographique et un sujet d'étude spécifique (par exemple, une télévision) est, par là même, soulevée. Les objectifs sous-jacents aux EAMs sont également remis en question par la mondialisation. Quelle est la perspective fournie par les EAMs et celle-ci est-elle en adéquation avec les objectifs de durabilité, qui s'inscrivent au niveau mondial? L'extension des EAMs telle qu'elle est actuellement envisagée dans les divers projets de recherche, c'est-à-dire avec une meilleure modélisation des importations, est-elle suffisante ou une « vraie » vision mondiale est-elle souhaitable? Nous décrivons cette « vraie » vision mondiale comme une vision qui ne soit pas européo-centrée mais qui donne la même importance aux problèmes environnementaux quelque soit leur situation géographique, une vision qui considère le local au cœur du global, c'est-à-dire, concrètement, une vision qui rapporte au niveau agrégé les problèmes locaux clés, même s'ils sont secondaires au niveau global.

La classification des EAMs se basant sur la description de ce qu'elles sont à l'aide des trois propriétés que sont: l'échelle de l'indicateur final, la conception de la méthodologie et l'objectif environnemental, nous permet de tirer les premières conclusions quant à la manière dont les EAMs font face aux attentes et défis mentionnés précédemment. Nous constatons que les EAMs actuelles ne proposent pas, ni individuellement, ni en tant que groupe, une vision multi-critères, multi-échelles cohérente. L'échelle des entreprises, de même que l'utilisation des ressources en eau et en sol, sont, par exemple, particulièrement peu considérées. Aucune EAM ne peut, par ailleurs, s'appliquer d'une échelle micro à une échelle macro de manière robuste et, bien que des ponts entre échelles proches puissent être établis, une vision cohérente du micro au macro n'est pas encore atteignable. Bien que la classification établie puisse être affinée, nous constatons également que plusieurs EAMs traitent des mêmes sujets. L'étude des complémentarités et substitutions possibles entre EAMs semble ainsi souhaitable afin de diminuer les futurs besoins en données et modèles. Cette suggestion, bien qu'apparaissant comme évidente, n'est pourtant pas encore à l'ordre du jour des agendas de recherche.

L'étude des diverses EAMs au sein du projet IMEA nous a permis d'établir un archétype de la démarche suivie lors d'une évaluation effectuée avec une EAM. Ce schéma est composé de cinq étapes et quatre résultats intermédiaires. Les deux premières étapes, la conception du système, ainsi que les collecte et préparation des données, fournissent le premier résultat intermédiaire : un inventaire de type direct. L'étape suivante, dénommée allocation, vise à réallouer les flux de l'inventaire direct selon une perspective de cycle de vie mondiale, donnant lieu à un second inventaire. L'étape suivante, dite d'agrégation, consiste à réduire la complexité de cet inventaire par la génération d'un, ou de plusieurs, indicateurs synthétiques en se basant sur des hypothèses de similarité. Cet indicateur est ensuite comparé à des références, internes ou externes, pour fournir un indicateur de performance.

L'évaluation de la satisfaction des attentes et des défis par les EAMs, à chacune des étapes de la démarche, nous permet de dresser le constat suivant. Les EAMs forment un groupe hétérogène au niveau des résultats intermédiaires délivrés, qui peine à fournir une réponse conforme aux besoins des décideurs et à répondre aux défis de la mondialisation. L'inventaire direct est le résultat intermédiaire le plus commun. Il est généralement réalisé correctement, sauf dans le cas de l'empreinte écologique. L'inventaire mondial selon une perspective cycle de vie n'est atteignable de manière satisfaisante que par deux méthodes : LCI (life cycle inventory en anglais) et PIOT. La méthode IOA permet certes une prise en compte des chaînes de production-consommation au niveau mondial, mais cette allocation est de type monétaire, de qualité peu satisfaisante dans certaines situations. La qualité des indicateurs synthétiques générés dépend de la robustesse des schémas d'agrégation, plus grande au niveau des pressions que des impacts. Les indicateurs de performance sont clairement le point faible des EAMs. Cinq approches proposent une comparaison avec des références internes ou externes: HANPP, ALD, WF, EF et LCIA (life cycle impact assessment en anglais), mais la pertinence des références est variable.

L'hybridation (ou combinaison) des EAMs permet d'améliorer la qualité de la réponse apportée actuellement mais introduit d'autres difficultés. La principale forme d'hybridation est, en effet, envisagée avec les modèles entrées-sorties (IOA). Outre la possible insatisfaction du schéma d'allocation monétaire mentionnée précédemment, d'autres aspects sont à relever, comme la qualité questionnable des données du commerce international ou les hypothèses sous-jacentes à la modélisation formelle des importations dans les modèles MRIO (multi-regional input-output models en anglais). Nous estimons qu'actuellement du moins, ces modèles entrées-sorties sont cependant un élément indispensable à toute évaluation prenant en compte la mondialisation. Divers points nécessitent de plus amples recherches, comme le lien entre les prix et les quantités ou la manière de représenter les structures de production et technologiques dont l'évolution est rapide, et il faut davantage indiquer leurs limites, comme, par exemple, leur incapacité actuelle à délivrer une évaluation au niveau de biens et services spécifiques.

Nous faisons dans cet article, une première proposition de grille d'analyse synthétique, permettant l'analyse de toute EAM. Elle comporte trois axes représentant chacun un objectif : l'aptitude à la comptabilité environnementale, l'aptitude au processus décisionnel et le potentiel d'amélioration. Chaque axe est composé de plusieurs dimensions (huit au total), découpées en thèmes (22 au total). Le premier axe contient les dimensions relatives aux qualités inhérentes d'une EAM, à sa maturité et son auditabilité ainsi qu'à sa capacité d'adaptation aux défis de la mondialisation. Le deuxième axe concerne le potentiel d'utilisation d'une EAM ainsi que son potentiel analytique et son potentiel en terme de comparabilité des indicateurs et de l'intégrabilité de son cadre de comptabilité. Le dernier axe exprime le potentiel d'amélioration pour chacune des dimensions mentionnées ci-dessus.

La mise en place de ce cadre d'analyse, et l'analyse des EAMs, montrent que les développements futurs requis pour l'intégration des défis liés à la mondialisation pourraient être facilités par *i)* le développement de profils de produits et de régions afin de déterminer quelles sont les données pertinentes à développer selon le contexte, *ii)* la concentration des efforts de recherche sur quelques EAMs, pertinentes à chaque contexte, plutôt que d'effectuer un développement parallèle de toutes les méthodes à l'échelle mondiale, et *iii)* l'adoption d'une approche modulaire, telle que suggérée par la démarche en étapes proposée ici, permettant la collaboration entre spécialistes des différentes EAMs sur des problèmes communs afin d'adapter les meilleures solutions de manière transversale.

ARE ENVIRONMENTAL ACCOUNTING METHODS MEETING SOCIETAL EXPECTATIONS AND CHALLENGES IN A GLOBAL ECONOMY?

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INTRODUCTION

Human activities influence the environment, the magnitude of changes being locally-dependent. There is a need to quantify this influence in order to support decision processes in policy-making, in corporations and for citizens. Environmental accounting is a means to measure these interactions between the environment and the socio-economic sphere, such as the quantities of energy, matter and water used, climate change or impacts of pollutants on ecosystems, for all scales relevant in a decision-making process.

A number of Environmental Accounting Methods (EAM) has been developed so far: the differences in methodologies and data sets reflect the diversity of objectives and scales of analysis in environmental accounting. Each EAM has specificities resulting in its own strengths and weaknesses. All EAMs are nevertheless currently facing the same new challenges from the globalization of the economy. Analyses of environmental sustainability demands an interregional analytical framework (Kissinger & Rees, 2009): sustainability anywhere is linked, directly or indirectly, to sustainability elsewhere. Similarly, all EAMs face the same societal expectations including the provision of an adequate coverage of environmental preoccupations with scientifically valid indicators that can be further used in existing tools for decision-making.

The challenge of globalization advocates for the adoption of a so-called “true” global vision. This vision acknowledges that a sound development requires more than the straightforward extension of existing environmental assessments, e.g. of products or nations, to consider foreign impacts with a proper modelling of imports. Sustainable development is explicitly concerned with defining social welfare goals (Ekins *et al.*, 2008) and these goals are global as shown by the adoption of the United Nations Millennium Declaration (United Nations, 2009). A straightforward extension would only be equivalent to implicitly adopting an importing country perspective, e.g. a European-centered perspective in the case of Europe. This appears inappropriate in a global vision because it does not put emphasis on local environmental problems even though these problems are among the first consequences of the production of traded goods. On the contrary, a global vision leads, for example, to recognizing that the acuteness of environmental issues differs according to local environmental and socioeconomic conditions. Consequently, this vision questions the choice of a particular EAM: is this EAM applicable and relevant to a particular scope, scale, or location… This vision also questions the feasibility and wish of obtaining valid assessments at worldwide scale for each of the existing EAMs considering the large costs of data collection and processing as well as modelling issues. Providing an answer to this questioning is difficult today and requires a better understanding of the abilities of EAMs.

The global aim of our paper is to provide elements to answer the following question: "Does a given EAM meet societal expectations and how does it cope with new challenges from globalization?" One possible answer to the question would have been to perform a detailed analysis of each EAM separately. We have opted here for a more synthetic analytic approach. We firstly detail the expectations and challenges faced by EAMs (section 2). These expectations and challenges affect EAMs at each step of their workflow realisation; consequently, we have performed a meta-analysis of current EAMs and subsequently, identified the main characteristics of EAMs with respect of "what" they are (section 3) and "how" they work (section 4). For each characteristic, we identify the various answers brought to expectations and challenges and their level of satisfaction. We obtain a descriptive framework that brings a structured answer to how the identified expectations are met and challenges are tackled for any EAM. This framework is used in section 5 to perform a global analysis of several EAMs and conclude on the general fulfilment of expectations by EAMs and how they cope with challenges from globalization. We propose then a grid for reporting on these aspects for any EAM in section 6. This grid is built around three axes: accounting abilities, decision-making abilities, and improvement potential. Concluding remarks are then provided in the last section.

Our work is a meta-evaluation of the performance of EAMs, as defined and applied for example to sustainability indicators by Ramos & Caeiro (2009). This work complements, with an analytical perspective, the current development of environmental accounting methods towards the inclusion of non-domestic environmental impacts with a proper modelling of imports like in multi-regional approaches (Hertwich & Peters, 2009; Tukker *et al.*, 2009) or towards combining different EAMs (Kytzia, 2009; S. Suh *et al.*, 2004; Wiedmann, 2009) to go beyond known limitations of current EAMs.

This discussion is based on the results of the IMEA (IMports Environmental Accounting) SKEP-Eranet project lead by MINES ParisTech/ARMINES with partners from Institute of Social Ecology (Austria), TNO (The Netherlands), University of Oulu (Finland), and VITO (Belgium), aiming at assessing the potential of EAMs for describing the environmental requirements of European imports

(Blanc *et al.*, 2009). To ensure a structured and comprehensive coverage of the issues, a detailed questionnaire has first been developed and filled for each of the EAM based on expert knowledge and literature reviews. The questionnaire was based on 55 questions combined in seven categories. Results have then been discussed in a workshop with other experts from statistical offices and environmental agencies, researchers and environmental accounting specialists, held in Paris, March 20th 2009.

CONSTRAINTS FROM SOCIETAL EXPECTATIONS AND CHALLENGES FROM GLOBALIZATION

SOCIETAL EXPECTATIONS

Societal expectations towards EAMs are framed by expectations towards environmental assessments, themselves framed by the concept of sustainable development. This concept states that the three dimensions (environment, social and economic) of society should be considered of equal importance and that a coherent vision considering them individually, and in their interactions, should be aimed at (World Commission on Environment and Development, 1987) although integration remains a medium- to long-term objective.

The first set of expectations and of subsequent operational constraints results from the search for coherence in the implementation of this concept. A coherent vision calls for integrated, or at least compatible, accounting frameworks allowing a comparison of indicators calculated in the three dimensions. Accounting frameworks should also evidence interactions between these dimensions (Ness *et al.*, 2007). The linkage between human activities and environmental impacts has, for example, been explicitly modelled by the DPSIR model adopted by the European Environment Agency (EEA, 1997). Based on a chain of causality, it links human Driving-Forces to Pressure on the environment, changes of environmental State, resulting Impacts on ecosystems, individuals or communities and eventually human Responses to correct the situation. Svarstad *et al.* (2008) show the limits of this framework used to provide and communicate knowledge on the state and causal factors regarding environmental issues.

The modelling of linkages is also desirable in socio-economic activities. A systemic view like a life cycle perspective helps in better estimating impacts of entities, activities and products. Lenzen *et al.* (2007) show how this view can provide different schemes to attribute responsibilities. The European Union is, for example, increasingly adopting plans and policies based on such perspective, e.g. the Sustainable Consumption and Production and Sustainable Industrial Policy (SCP/SIP) Action Plan (European Commission, 2008). A life cycle perspective allows the quantification of the total environmental load of a socio-economic activity by accounting for the direct, upstream and downstream environmental loads along the whole production-consumption chain of an activity (ISO, 2006a). This perspective is unusual for socio-economic indicators, which leads to difficulties for comparing indicators between dimensions.

Coherence is also attained by measuring environmental pressures using multiples measures at multiple scales, as reflected in the definition of environmental accounting by the United Nations Statistics Division. The United Nations (1997) describe environmental accounting as physical and monetary accounts at the national and corporate levels. The U.S. EPA (Spitzer & Elwood, 1995) or the BSI (2008) extend this definition further in order to deal with other objects, such as products and services. Environmental Accounting is however only one of the several strategies followed for assessing the environmental dimension of sustainable development. These strategies differ in the degree of comparability between their indicators but all recognize the need for multiple environmental measures covering energy, material, water and pollutant flows. Assessments range from sets of heterogeneous indicators on key environmental issues, e.g. the EEA core set of indicators (EEA, 2005) or the United Nations indicators of sustainable development (UNCSD, 2001) to approaches incorporating environment aspects into existing economic assessments to deliver a unique indicator, like the green GDP or the Genuine Progress Indicator (Daly & John B. Cobb, 1989; Dasgupta, 2009). Semi-integrated accounting frameworks, like the Integrated and Economic and Environmental Accounting (SEEA) (United Nations, 2003) represent the middle way: they extend existing economic accounts with satellite accounts sharing the same structure. Mayer (2008) and Singh *et al.* (2009) review a large number of sustainability assessment methodologies, broader than the environmental dimension. Bebbington et al. (2007) describe approaches in monetary terms like the Sustainability Assessment Models.

The second set of expectations comes from the objectives of accounting frameworks to provide valid indicators (Nardo *et al.*, 2008) and the abilities of the latter to undergo further analyses. Environmental accounting frameworks are expected to provide a theoretically sound and synthetic view of the high number of environmental flows induced by the socio-economic sphere. The overall methodological soundness of an EAM, *i.e.* the scientific validity of its principles and methodological steps underlying the construction of a final indicator as well as its acceptance by the scientific community, are thus crucial societal expectations. Beyond their use as a "descriptive […] structured body of information that describes a system", EAMs are also expected to extend this neutral representation of past facts with additional assumptions for delivering analytical tools for decision-making (de Haan, 2001; Peskin, 1998). Pedersen & de Haan (2006) show how physical flow accounts based on national accounts can provide analytical advantages. The ability of EAM results to undergo further analyses like causal analysis, path analysis (Fernandez-Vazquez *et al.*, 2008) or structural decomposition (Wier,

1998) permits to reveal the main components of, and the causes behind, an aggregated indicator describing a complex system, increasing the potential for decision-making.

Finally, expectations are expressed on the usability of an indicator for decision-making. An indicator is of practical use for decision-making if it is relevant with respect to objectives, intelligible, delivering a clear message and accepted. In addition, results should be reproducible according to common guidelines by statistical offices, timely and cost-effective (Nardo *et al.*, 2008; Wiedmann *et al.*, 2009). Intelligibility means that an indicator can be understood without difficulty by decision-makers, citizens and consumers; it is related to the message of the indicator and to its units. Univocity is a characteristic related to the clarity of the message delivered by an EAM to decision-makers. A message is clear when the message can be interpreted as good or not good. An unclear message can be due e.g., to multiple indicators showing contradictory signals in the case of multi-criteria assessments, or indicators not related to any reference value. Univocity is thus here traded-off against a larger coverage of environmental issues represented by multiple indicators: univocity may mask the true complexity of environmental challenges. The acceptance of an indicator helps its implementation and its establishment as a reference. Acceptance refers here to the acceptance by the political, economic and social actors. Ease of use is an essential characteristic since EAMs are based on a complex workflow for computing one or several final indicators. This implementation is expected to be feasible by public bodies in order to ensure their involvement and therefore the indicators effectiveness. This implementation should not rely on scientists only, in order to fully implement the passage from science to application and ensuring a large dissemination.

These three sets of societal expectations (sustainable development, accounting and decision-making) comprise nine societal expectations summarized in Table 1 (left part). These nine expectations are labelled *exp. 1* to *exp. 9* in the rest of the paper. In regard of the expectations, this table lists also the challenges from globalization that are discussed hereafter. These expectations and challenges represent the constraints faced by assessment methodologies to achieve the purposes of sustainability assessments as defined by Kates *et al*. (2001): ”the evaluation of global to local integrated nature-society systems” (Singh *et al.*, 2009).

		Societal expectations	Main challenges from globalisation
	1	Comparability -> integration with indicators and accounting frameworks	Comparability within an interregional accounting framework
	2	Explicit linkage between socio-economic activities and the environment	Cross-boundary pollutant transfers & regional impact computation
	3	Life Cycle perspective	Global chains
	4	Multi-criteria/indicators perspective	Regional significance of criteria, new criteria (e.g. water)
SD	5	Multi-scale perspective	Relevance of scales & bridging between scales
	6	Soundness (theory, models and data)	Soundness of imports assessment (production and trade)
Accounting	7	Analytical capabilities	New analytical capacities to answer globalisation issues
	8	Usability of indicators	Cost-effectiveness of global indicators
Decision-Making	9	Relevance to objectives	Europeo-centered or "local in global" perspective

Table 1. Summary table of main societal expectations and challenges from globalization faced by EAMs. SD stands for Sustainable Development.

CHALLENGES FROM GLOBALIZATION

Challenges from globalization, labelled *C1* to *C9* hereafter, are affecting EAMs in their ability to report on sustainable development, accounting and decision-making capabilities. As the world economy evolves towards more integration, production-consumption chains are becoming international and even global due to the dynamics of relocation (off-shoring) and reorganization (outsourcing) of activities (Abonyi, 2006). This integration results in a parallel shift of environmental impacts. Ghertner & Fripp (2007) evidence, for example, the shift associated with the goods consumed in the USA to other countries through trade. Consequently, there is a need for an interregional accounting framework and a life cycle perspective in this context must be global and should consider this geographic fragmentation (C3).

Kissinger & Rees (2009) identify the needs to quantify inter-regional relationships: *i)* the volume of material exchange between regions, *ii)* the quantities of physical inputs employed to produce goods for trade and *iii*) the direct & indirect negative ecological impacts on the producer and exporter. We generalise these needs as needs for a proper modelling of international transport, international trade in goods and services, and regional production structures with their inputs and outputs flows. A large amount of data and new models are thus required. Due to their global reach, these data and models differ in availability and in quality, affecting the robustness of EAMs results. This is the challenge C6 “soundness of imports assessment”. The computation of the relevant ecological impacts is the challenge C4. As mentioned in the introduction, globalization implies the development of indicators which were not crucial in a European context but are crucial for some new trading partners, like water footprints, which are currently entering into a first phase of normalisation (Chapagain & Hoekstra, 2008). This computation requires, for some EAMs, to handle two more key features: the cross-boundary transfer of environmental flows through environmental media (air, water and soil) and through additional pathways like food products, as well as the foreign/regional characteristics of the regions of impact (C2). Jolliet *et al*. (2008) show that the magnitude of global pollutant transfers through food is comparable to air transfer for some pollutants. Huijbregts (1998) and Potting & Hauschild (2006) describe that methodological variations and local specificities result in up to three order of magnitude for acidification and eutrophication between European regions. Globalisation thus requires regional information. Some EAMs, like the Human Appropriation of Net Primary Production (HANPP) are inherently regional since built on geo-referenced data sets (Haberl *et al.*, 2007) but most of them require specific developments, which are still in infancy. Mutel & Hellweg (2009) show how to regionalise life cycle assessments with existing data sets based on available geographic information. Raugei & Ulgiati (2009) show an example of accounting with a global perspective for Life Cycle Assessment (LCA) and Material Flow Analysis (MFA) but however without location-dependant data. Finally, though not only originating from globalization, an essential challenge (C1) is the compatibility and comparability of indicators from this interregional accounting framework with existing indicators.

Reporting is intrinsically linked to objectives and underlying values since ‘indicators arise from values and create values’ (Meadows *et al.*, 1972). The definition of these objectives and the implementation of a “true” global vision is a challenge for decision-makers, particularly in western economies, but also for the developers of EAMs. Should europeo-centered indicators be designed or should a truly global perspective be adopted (C9)? Should methodologies be modified to allow evaluating and reporting on these locally important environmental issues even if they are not perceived as key issue when looking at aggregate measures? How to model and represent this so-called “local in global” perspective? De Haan (2002), proposes an overview of indicators designed to measure the indirect requirements of a national economy including cross-boundary transfers of environmental flows, as well as a comprehensive 'environmental balance of trade' of the Netherlands.

As a result of the large amount of additional data and models needed, the cost-effectiveness of EAMs is an important issue (C8). Recognising that not all indicators are relevant in each region at each scale, some thinking seems to be required on the identification of the complementarities and redundancies between existing EAMs as well as on the scope of relevance (scale and region) of each EAM (C5). Best *et al.* (2008) compare, for example, the existing indicators of land use for the European Commission. In other words: should everything be measured everywhere at every scale or should assessments be adapted to local conditions, scales and goods specificities, hence to local and good environmental profiles? In addition, is it possible to reduce data needs by establishing bridges between scales to re-use existing databases or results from studies?

Eventually the question of the capacity of existing analytical tools provided by EAMs to answer these questions and others in a context of globalization should be asked (C7). Should new solutions be developed in addition to data sets and models to be able to tackle the challenges from globalization or are existing ones adequate? New approaches are apparently needed in some EAMS: Peters & Hertwich (2006) propose a path analysis on Multi-Regional Input-Output models to provide linkages between the global production networks linking consumption and production. Friot & Antille (2009) propose an underlying flow decomposition to analyse the structural causes of emissions within an MRIO model.

ENVIRONMENTAL ACCOUNTING METHODS: WHAT THEY ARE

Environmental Accounting Methods (EAMs) are not defined in a formal way. We propose here a definition based on the discussion on expectations from the previous section. EAMs are defined as any accounting methodology allowing quantifying, synthesizing, analyzing, comparing and communicating the environmental performance, expressed in physical terms, of any activity, or group of activities, according to a life cycle perspective in a way that is suitable for decision-making. We describe now what EAMs "are" and their subjects with three properties relevant to our purpose: the scale of their final indicators, the methodology design of socio-economic entities and activities, and the environmental focus.

The scale of final indicators depends on the main objective for which an EAM has been initially designed. Environmental accounting methods are applied for monitoring and managing the environmental performance over time of a large range of subjects: entities and the outcomes of their activities, e.g. products and services. We group these entities into three categories: political entities bounded by geographic boundaries, economic entities and social groups. Each category is split into three scales: the macro-scale, the "upper-meso-scale" and the "lower-meso-scale". The macro-scale consists of nations, domestic economies and populations; the upper-meso-scale consists of regions, sectors and sub-populations groups, while the lower-meso-scale consists of smaller regions or cities, companies or sites and people or households, as shown in Table 2. We reserve the "upper-micro-scale" to describe production processes. Outcomes such as products, products services, and tertiary sectors services are at the "lower-micro-scale".

	Socio-economic entities			**Activities outcomes**
	Political	**Economic**	**Social groups**	
Macro	Nation	Domestic economy	Population	
Upper-meso	Region	Sector or industry	Sub-population	
Lower-meso	Small region	Company / site	Individual / household	
Upper-micro		Production processes		
Lower-micro				Products, products services, tertiary sector services

Table 2. Classification of subjects of EAMs, grouped by type (entities and outcomes) and scale.

The methodology design of socio-economic entities and activities in EAMs takes two ways: top-down and bottom-up, meaning a way downward or upward in scale. Top-down approaches begin at the highest level, formulating first an overview of the system, specifying but not detailing any first-level sub-systems. Each sub-system is considered as a “black box” which can be refined in greater details. Due their high level of aggregation, these approaches are mainly applied to describe large entities, at macro- or meso-scales and in the case of the description of an entire system, can provide assessments characterized by completeness. The coherence when dealing with lower scales is ensured through the availability of macro-scale totals. Bottom-up approaches are taking the opposite approach. They piece together detailed systems to give rise to larger ones; the original systems become sub-systems of the emergent system. Very detailed and accurate if based on reliable data sets, these approaches are however incomplete by essence since a limit has to be set, with a cut-off rule, on what to include in the analysis, leaving out some elements. The difficulty to guaranty the coherence of an assessment performed by adding results based on bottom-up approaches is a well know issue. Lenzen (2008) lists a number of policy and decision-making frameworks that make use of life cycle techniques, where this double-counting error is highly undesirable and proposes a potential solution to this double-counting problem.

Entities and activities generate environmental flows subject of the “environmental focus” property. These flows are numerous and multiple classifications exist. OECD (2008a) proposes a usual two-categories classification: “resources-oriented” and “pollutants-oriented”. We extend this classification by splitting resources-oriented approaches into three categories: “mineral and fossil fuels-resources”, “land and biomass” and “water”. We also include specifically carbon emissions by adding a fifth category, that we call “global warming-oriented”. All five categories bring complementary information in multi-criteria assessments. Pollutant-oriented approaches deal with flows of substances, e.g. chemicals or heavy metals, into air, water and soil. Global warming-oriented approaches account for greenhouse gases and their global warming potential: they are currently the most used approaches.

We propose a classification of the most used EAMs using the three properties (scale of final indicators, methodology design and environmental focus) and comment on insights that can be earned from this classification regarding expectations and challenges faced by EAMs. The analysed EAMs are listed in Table 3. Included are Life Cycle Assessment, Economy-Wide Material Flow Analysis, Physical Input Output Tables, Material Inputs Per Service Unit, Environmentally Extended Input-Output Analysis, land use indicators like the Human Appropriation of Net Primary Production, the Actual Land Demand or the Ecological Footprint, the Water Footprint, and the so-called “Corporate Carbon Footprints” based on GHG accounting. Finnveden & Moberg (2005) propose another classification of most of these EAMs based on their characteristics, the type of impacts included, their object of study and whether these studies are descriptive or change-orientated. We do not include here any EAM based on the combination of EAMS, also called hybrid methodologies, developed to overcome EAMs limitations.

Acronym	Full name
LCA	Life Cycle Assessment
EW-MFA	Economy-Wide Material Flow Analysis
PIOT	Physical Input Output Tables
MIPS	Material Inputs Per Service Unit
EE-IOA	Environmentally Extended Input-Output Analysis
HANPP	Human Appropriation of Net Primary Production
ALD	Actual Land Demand
EF	Ecological Footprint
WF	Water Footprint
CCF	Corporate Carbon Footprints

Table 3. List of the EAMs analysed with acronym.

The results of the classification are reported in Table 4. For each cell, we indicate which EAMs have been designed for the specific values taken by each of the three properties: scale of the final indicator, methodology design and environmental focus. The literature reports applications of EAMs at scales close to those for which they were initially designed; in that case, it is assumed that the original assumptions hold though less accurate and consequently, the use of such EAMs is still valid. These cases are indicated by small-scale italics. Grey cells indicate the absence of specifically-designed EAMs.

		Mineral and fossil fuels resources	**Land & biomass**	**Water**	**Global Warming**	**Pollutants**
Top-Down	macro	EE-IOA, EW-MFA, PIOT	EW-MFA, EF, HANPP, ADL	WF	EE-IOA, EF	EE-IOA
	upper-meso	EE-IOA, PIOT	EF, HANPP		EE-IOA	EE-IOA
	lower- meso	*EE-IOA*			*EE-IOA*	*EE-IOA*
	upper-micro					
	lower-micro					
Bottom-Up	macro		*EF*	*WF*		
	upper-meso		*EF*	*WF*	CCF	
	lower- meso	*LCA, MIPS*	*EF*	*WF*	CCF, *LCA*	*LCA*
	upper-micro	LCA, MIPS	LCA, *EF*	LCA, WF	LCA	LCA
	lower-micro	LCA, MIPS	LCA, *EF*	LCA, WF	LCA	LCA

Table 4. Classification of EAMs based on the three properties: scale of the final indicator, methodology design and environmental focus. Small-scale italics indicate applications of EAMs found in the literature that are at scales for which they were not initially defined. Grey cells indicate the absence of specifically-designed EAMs.

The large number of grey cells in Table 4 shows a lack of adequate coverage for some environmental issues at several scales: a fully coherent multi-criteria multi-scale perspective is not achieved by any EAM neither by the ensemble of EAMs.

A second observation arising from this classification is that none of the EAM except for the Ecological (EF) and Water Footprints (WF) has been designed for assessments from upper-micro- to macro-scale. These two applications have however been recognised as lacking robustness and are being replaced by top-down approaches for assessments at macro-scale (Hoekstra, 2009). Among the top-down EAMs, only EE-IOA and PIOT are effectively top-down since providing indicators at several scales. EW-MFA and land use indicators (EF) could be extended to lower scales by combining them with EAMs providing an internal description of socio-techno-economic relations like EE-IOA like in (Giljum *et al.*, 2008) and in (Turner *et al.*, 2007). LCA also include such a detailed description of a system within a bottom-up approach. Both EE-IOA and LCA can be applied at different scales and be complemented with any type of environmental flows: material, land, water, carbon or pollutants. While LCA is already including many of these flows, this is still not the case for EE-IOA, except in some countries like the USA (Suh, 2005) but development is undergoing (Tukker *et al.*, 2009). Considering the environmental factors used in EAMs, rather than the description of socio-economic economic entities and activities, provide however another picture. The EF and MIPS use national factors at the "bottom-up" levels and are thus not truly bottom up, but in fact top down applied to smaller scales. LCA is similar for some processes like electricity mixes. Indeed, none of the methods except HANPP use regionally appropriate information and can thus be applied at the regional level based on regional data.

A third observation is that the lower-meso-scale, i.e. the scale of companies, is not the original focus of any of the methodologies except for Corporate Carbon Footprints. This reflects the complexity of making an assessment with a life cycle perspective at company level and the lack of interest, up to recently, for methodology development at this scale (Wiedmann *et al.*, 2009). The only standardised and robust Corporate Carbon Footprints (CCF) are focusing on direct emissions (except for electricity) only (WRI & WBCSD, 2004). Schaltegger & Burritt (2000) describe concepts and issues of environmental accounting at the corporate level.

While some bridges can be established to overcome the lack of data at given scales, for example between macro- and upper-meso-scales in the case of top-down approach, or between lower- and upper-micro-scales in the case of bottom-up approach, the bridge with lower-meso-scale cannot be achieved in any case without strong assumptions. Bottom-up approaches are often used for the description of specific products and services. Going upwards in scale requires designing generic groups of products at lower-meso-scale and identifying a representative specific product for each of them. This generalization of specific results can however be inaccurate unless the specific goods described are close to the expected average of the groups. Top-down approaches face the opposite problem: they can deliver information up to a generic group of products but the linkage with specific products is difficult because of the diversity of products included within a group, even with very detailed top-down approaches (Tukker *et al.*, 2006).

A last observation is that several scales and environmental focus are dealt with by more than one EAM in Table 4. While this classification could be refined in this purpose, it shows which EAMs may compete with each other since they deal with the same type of flows: substitutions between these EAMs may be further researched. On the contrary, others EAMs should probably be used together in a basket of indicators since they provide complementary information.

ENVIRONMENTAL ACCOUNTING METHODS: HOW THEY WORK

We concentrate now on the characteristics of "how" EAMs work and how they meet expectations and challenges with the help of an archetypical EAM workflow covering all steps required from EAMs to meet these expectations. This workflow, shown in figure 1, draws on, and extends, the description of a Life Cycle Assessment (ISO, 2006a) and the approach by Mayer (2008) to analyse issues of sustainability indices.

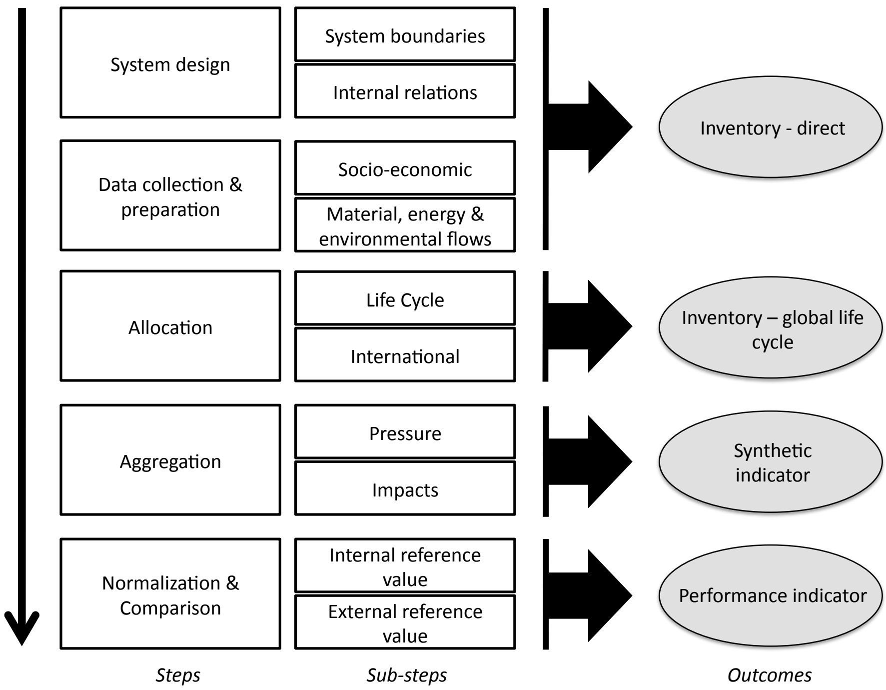

Figure 1. Archetypical EAM workflow. Steps and sub-steps are described on the left part of the scheme and the resulting outcomes on the right.

Four possible outcomes of EAMs, resulting from the explicit or implicit application of five steps, are considered. The first outcome is an "inventory – direct". This inventory is a collection of heterogeneous flows of the "direct" type, i.e. a classical inventory by source. This inventory is completed once the "system design" (step 1) and the "data collection and preparation" (step 2) are completed. Information from this inventory can then be re-allocated along global production-consumption chains in step 3 “allocation” based on internal relations from the system. This results in a global inventory with a life cycle perspective (outcome 2 “inventory - global life cycle”). In order to reduce the complexity and heterogeneity of the available information, one or several “synthetic indicator” can be generated by aggregating flows at the level of Pressure or Impacts (step 4). Eventually, the aggregated indicator is compared to reference values in the last step “normalization & comparison” (step 5), resulting in a “performance indicator” to ease decision-making.

SYSTEM DESIGN

“System design” consists in describing the socio-economic system considered in the assessment of an entity or the outcome of an activity. The system boundaries must consider environmental-society interfaces and boundaries between societies. Setting the boundaries of a socio-economic system determines the type of environmental flows that should theoretically be included in an inventory to eventually compute an indicator that is assumed representative of the system described. The relations within a socio-economic system describe how the components of a system are connected through their inputs and outputs.

System design plays a key role since it influences the rest of the EAMs steps, and thus their capacity to meet expectations. Expectations of soundness (exp.6 in Table 1) and comparability (exp.1) in a modelling context, i.e. a context characterized by simplification and truncation are described here. The expectations of a life cycle perspective (exp. 3) and analytical capacities (exp. 9), also strongly influenced by the system design are described in other steps.

A review of the problems of setting boundaries is provided for LCA and Input-Output Analysis by Reap (2008a). We add here additional elements related to the type of rationales applied to set boundaries between socio-techno-economic activities and issues linked to boundaries between these activities and the environment.

Two types of rationales can be applied to set boundaries: physical and socio-economic rationales. Physical rationales are usually established specifically for environmental assessments, e.g. in the ISO 14044:2006(E) for LCA (ISO, 2006b). Suh *et al.* (2004) recommend to set cut-off criteria depending on the importance of the expected contribution of an activity to the total environmental load, mass or energy within a system. The cut-off is thus applied at the “end” of production chains (upstream or downstream). On the contrary, socio-economic rationales used in approaches like IOA have other original aims; since their original goal was a representation of the economic system alone, the environmental relevance of their system boundary must be considered. In IOA for example, boundaries are set between the activities of economic and non-economic agents or between observed and non-observed economy, i.e. underground, illegal or informal activities (OECD, 2002). If a large informal economy is not included, the level of truncation of the modelled system may therefore be large and not be environmentally relevant. In a context of globalization, where underground activities can be a large part of some developing economies, and thus of related environmental flows, this aspect increases in importance. This issue adds to the challenge of setting proper geographic boundaries in top-down approaches that Lenzen (2001) qualifies as potentially as important as issues linked to cut-off in bottom-up approaches.

Comparability between indicators is possible when the indicators cover the same underlying reality: their system boundaries with respect of socio-techno-economic activities are consistent with one another. Indicators at macro- and upper-meso-scale can be compared between studies because boundaries of socio-economic nature are based on an internationally agreed framework, the System of National Accounts (SNA) (United Nations, 1993). The potential for comparisons at upper-meso-scale is however reduced for two reasons. First, the implementation of this framework varies between countries: the international classification of sectors ISIC is, for example, regionalised differently in the EU (NACE classification) and in the USA (NAICS classification) resulting in potential inconsistencies between studies based on these classifications. Second, even in the case of countries using the same classification, like NACE in Europe, similar activities are classified differently since economic structures are different: the degree of vertical integration of sectors influences, for example, this classification (Eurostat, 2001). International comparisons with monetary values also face the well-know issues of dealing with market exchange rates and purchasing power parities (Eurostat & OECD, 2006; Peters & Hertwich, 2007). In bottom-up studies, system boundaries that may be similar in theory are implemented on a case-by-case basis and comparability between different studies and with socio-economic indicators is thus strongly reduced.

The second type of boundaries, between activities and the environment is of importance when assessing the compatibility of resource-oriented accounting frameworks with economic frameworks. Several environmental resources are economic primary inputs and are thus accounted both in economic and environmental approaches. In the SNA, the limit between the national economy and the natural environment is defined by a distinction between produced assets, belonging to the national economy, and non-produced assets, part of the national environment. According to ESA (ESA 6.06) (European Communities, 1996), vineyards, orchards and any growing crops are thus produced assets: they are however considered as part of environmental flows by some resource-oriented EAMs like MFA, leading to potential inconsistencies.

DATA COLLECTION & ADAPTATION

The "data collection & preparation" step consists in collecting data on socio-economic activities and the related environmental flows, and adapting it to conform to the system description, to eventually generate the final data sets used for the assessment. Data sets can be generated for one or multiple periods. A reliable and complete final data set is a clear expectation for generating sound results with an EAM (exp. 6). Challenges from globalization question the usability of indicators (exp. 8) due to the already mentioned very large data needs. The reliance on few trade data sets of questionable reliability is also a challenge to overcome.

Final data sets are always an approximation resulting from multiple computations steps like the application of conversion factors, e.g. for the conversion from dry to wet biotic resources in MFA, or the matching between different classifications to join data sets, e.g. to go from categories of environmental requirements by source to categories related to socio-economic activities, or the use of proxies in case of missing data (Eurostat, 2003). The reliability and completeness, without gaps, of collected data as well as the robustness of preparation steps and their assumptions determine thus the reliability and completeness of the final data sets. Since these preparation steps are usually performed before practitioners use data, their documentation is important for evaluating the soundness of an indicator. The full documentation of these steps, including limitations, is however not current practice even if guidelines exist for some EAMs and some data sets include uncertainties. Some methods have been proposed to assess data quality, like the data quality matrix proposed by Weidema for LCA (1998) that could be used for this purpose. Björklund (2002) surveys approaches to improve reliability in LCA with uncertainty analysis and this survey is valid for other EAMs. The application of these methods is however not a current practice according to the literature and further developments are required to ensure that users have a proper understanding of the limitations of the indicators from EAMs.

A global perspective set new challenges for delivering such data sets by extending their spatial, temporal and technological coverage with respect of socio-economic activities and extending the type of flows included to better represent environmental concerns in developing countries. An extensive spatial coverage has two advantages. First, establishing assessments from the viewpoints of a large number of countries, and second a better modelling of traded goods by considering the characteristics of each country of origin along production chains. An extensive temporal coverage means a possible identification of time trends or up-to-date data sets through frequent updates. A frequent update is crucial for the evaluation of countries experiencing rapid structural, energetic or legal changes, or production activities based on emerging or fast evolving technologies like genomics or nano-technologies. A low spatial and temporal coverage may be compensated through modelling of missing data with detailed knowledge of the different technologies and their inputs, for example energy sources, and their outputs. An extensive spatial and temporal coverage is not yet the rule for both bottom-up and top-down approaches even if large efforts have been pursued in this direction for the last few years. Data is also lacking for many technologies, particularly new ones.

Reliability is particularly an issue in an international context because of the quality of trade data, an essential element of any top-down model. Trade data is among the oldest and better-collected data for custom taxes reasons. The development of bilateral trade matrices using databases from the OECD or the United Nations is however still a challenge. Inconsistencies are linked to the treatment of re-exports, inconsistent mirror trade, the conversion from product classifications to industry classifications, unallocated trade data (second-hand goods, waste), or issues related to the measurement of international trade in services as well as differences of definitions in compiling trade statistics (Gou *et al.*, 2009). Some authors like Fenestrate *et al.* (2005) have thus developed harmonised data sets that are freely available. Oosterhaven *et al.* (2008) and Bouwmeester & Oosterhaven (2008) developed a methodology to link these data sets to input-output frameworks. Few harmonised data sets are however available. As a result, all indicators including these data sets face the same, potentially important, limitations. In addition, an adequate treatment of some key issues, like the end-of-life stage or packaging, with global models is currently not possible. Dietzenbacher (2005) explains, for example, the limitations of waste treatment in monetary input-output models compared to physical input-output models.

ALLOCATION

The allocation step aims at applying a global, or at least international, life cycle perspective to a direct inventory to compute the total, i.e. direct and indirect, environmental requirements of some selected components within a system. Information on the direct inputs (e.g. use of materials, energy) and direct outputs (e.g. emissions) by the components of a system is here aggregated along global production-consumption chains by using the information on relations between these components.

This step is a direct implementation of the expectation of a life cycle perspective (exp. 3) and questions occur with respect of the expectation of soundness (exp. 6). We split the allocation step in two sub-steps to describe separately the capacity for implementing a life cycle perspective (allocation – life cycle) and the capacity for tackling the challenges of considering production chains on a global scale (allocation – international). Challenges from globalization are related to the soundness (exp. 6) of models and to the pivot role of goods and services for assessments at any scale (exp. 5).

Two types of allocations can be performed in this step: the virtual allocation of the embodied environmental requirements along a production chain (Ahmad & Wyckoff, 2003) and the effective transmission of the embedded, i.e. contained in a good, requirements along a production chain, like, plastic in a TV set or dioxin in prepared food products for example. The allocation of the embodied requirements represents the typical use of allocation, which is to compute the environmental load along a production chain up to a stage, e.g. resources requirements for producing a TV set.

Allocation – life cycle

The capacity for implementing a life cycle perspective depends on the necessary availability of the information on relations within a system, as mentioned under system design, and on the robustness of the so-called "allocation rules". A large stream of discussion has been undergoing in the life cycle assessment community on this type of allocation, summarised by Reap *et al.* (2008a).

A distinction between EAMs can thus be established on these two elements, the availability of relations and the robustness of allocation rules. First, some EAMs can integrate an allocation while other cannot. Macro-scale approaches do not model internal relations unless they are also designed for the upper-meso-scale. They can thus provide only a simplified life cycle perspective, distinguishing between direct and indirect environmental flows when data has been collected as such. Micro approaches, built-up around relations between elements are meant to provide a life cycle perspective, but may entail large extrapolation errors when their results are applied at a macro scale. Second, we propose to evaluate the robustness of the allocation, when it is feasible, by looking at the rationales used for splitting information at one point of a chain into the subsequent different downstream production chains. Two types of rationales can be used: physical or monetary rules. These rules are required each time an activity, e.g. cattle breeding, produces several products: milk, meat and skins in this case. In the case of embedded requirements, allocation should clearly follow a physical causality. On the contrary, several strategies using non-causal relationships based on physical and monetary rationales can be applied to allocate the virtual embodied requirements, resulting in different causal chains and responsibilities. Ekvall & Finnveden (2001) analyse these non-causal relationships for LCA and find that they do "…not accurately reflect the effects of actions".

Both physical and monetary rationales are currently used for allocating embedded and embodied environmental requirements. While physical rationales are usually preferred to monetary ones since they reflect the underlying physical flows better, monetary allocations are common for two reasons. First, they are adequate in the case of a co-production where the co-product is produced only because of the production of a main product having the main economic value. Second, they simplify the allocation procedure when monetary information is easily available. In the allocation of embedded requirements, monetary allocations are based on the strong assumption that they mimic physical relations. This is not always the case and is particularly inadequate when dealing with parts of production chains having a very low price, e.g. waste and goods for recycling. The same comment can be made when allocating embodied requirements with a monetary allocation unless the assumption is clearly made that causality and responsibility are well expressed by economic value. In our viewpoint, the choice of an allocation scheme is clearly subjective and linked to an objective. Since various objectives can be pursued, there is a need to inform on the objective since results can vary largely between allocation schemes.

Allocation – international

Globalization entails new allocation challenges. The robustness of international allocation depends on the availability and quality of data and models for estimating the embodied and embedded environmental requirements of imports. These estimates, as described in section one, are based on the modelling of foreign production structures and related flows, and on the modelling of trade, both of which present challenges.

At macro- and upper-meso scales, different strategies have been applied to overcome the lack of data with respect to foreign production structures when estimating the total requirements of imports; they differ in the amount of data used and in their robustness (figure 2). Weidman *et al.* (2007) and Peters *et al.* (2007) provide a review of the different types of strategies, based on IOA, used in this purpose. We draw on these descriptions here. The simplest strategy is to assume a similarity between foreign and domestic production and emissions structures (case 1 in fig. 2). This can be acceptable in the case of a large economy producing most of its inputs and for some type of assessments but is inadequate for a largely open economy where several extraction and industrial activities do not occur. Recent studies (Friot, Shacked *et al.*, 2009) have shown that this strategy is inadequate when performing an assessment at the level of impacts even for large economies with a low openness to trade. The three other strategies differentiate foreign production and emissions structures but differ in the way trade is considered: partial trade (case 2 and 3), and full trade (case 4). In the second strategy, production chains are purely domestic and the environmental requirements of exchanges are based on environmental trade balances. In the third strategy, international productions chains are partially modelled but only on a bilateral basis: this solution is adequate when the trade partners of the economy of interest are not trading a lot together and in a world without global production chains. The fourth strategy considers global production chains and is the most appropriate. Due to the increasing amount of data required from strategy one to four, the first ones have been largely privileged so far. Only few models (Multi-Regional Input Output models) are now considering global productions chains, listed in (Tukker *et al.*, 2009). These models are however relying on monetary rationales: limitations with respect of robustness previously mentioned apply thus here with some additional ones. First, these assessments are subject to the high variability of exchange rates. Second, the necessary use of nominal exchanges rates rather than purchaser power parities in these models renders even more apparent the potential inadequacy of a monetary allocation in an international context.

The modelling of trade is, in addition, still inadequate in this type of models because of the lack of information on the use of imported goods and services within an economy. Imports are usually allocated to industries by assuming a hypothesis of similarity between the products of different origins (Tukker *et al.*, 2009). Each sector importing the same good is thus importing the same modelled product that is a weighted sum of the different origins. The fact that industries are rather importing from a region rather than from another is therefore levelled out. The robustness of the whole international allocation is thus to be questioned and would benefit from studies on different countries and sectors. The lack of robustness of this allocation is particularly critical in some cases, for example when estimating the embedded transfer of pollutants through the food chain, requiring causal relationships, for an assessment at the level of impacts with a global perspective.

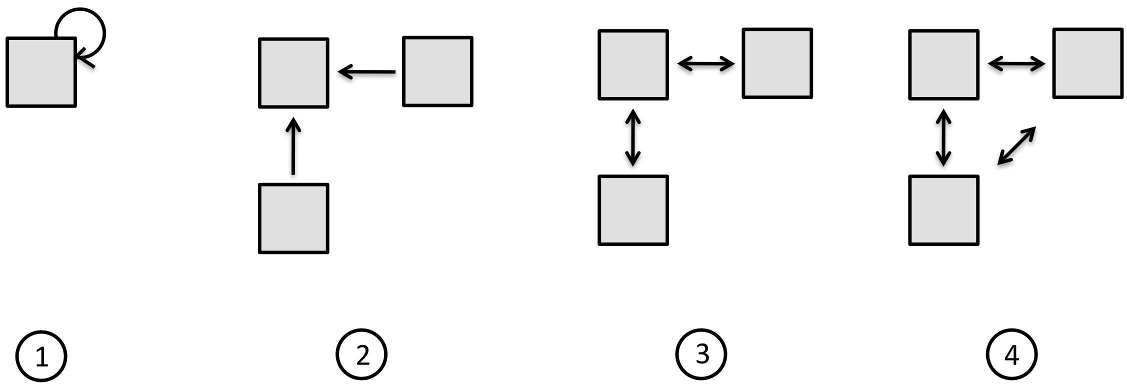

Figure 2. Four strategies of modelling global production chains. Boxes represent countries and arrows represent trade.

At micro-scale, the situation is not better because only few studies consider the global dimension explicitly, and only up to the second strategy in figure 2. In the first strategy, which is common practice, the same technology is assumed everywhere and the supply chain of foreign processes is similar to the domestic one. In the second strategy, different technologies are assumed but the full production chain of each of the inputs is thought of in terms of origin only: there are no international production chains. These international chains are introduced partially in strategy 3, and fully in strategy 4, which tremendously increase the amount of data required. As a result, while bottom-up studies are judged being more accurate than top-down approaches, this accuracy is however lowered in an international context with tightly integrated global production chains because of their large data needs which are usually not satisfied (Sangwon Suh & Huppes, 2005).

Interestingly, the extension of a life cycle perspective to a global scale is introducing a lower-micro-scale into macro-studies since the assessment of exchanges between countries requires the estimation of the total environmental requirements of traded goods and services. The modelling of traded goods and services affect thus the assessments at all scales. The consequence for purely macro approaches is that the robustness of the allocation mechanism they adopt influences the overall robustness of the method, particularly for originally physical based methods adopting an international allocation based on a monetary method like IOA which is the dominant one.

AGGREGATION: PRESSURE & IMPACTS

The aggregation step aims at reducing complexity by aggregating the heterogeneous environmental flows from an inventory to provide a synthetic indicator for decision-making (exp. 8). Most EAMs are designed to synthesize information from inventories through an aggregation of input and/or outputs into a reduced number of categories. This aggregation, whether implicit or explicit, is mostly performed with a weighted average of the various values as shown by (Singh *et al.*, 2009) in their overview of sustainability assessment methodologies. The robustness (exp. 6) of weighting schemes is the first concern (Nardo *et al.*, 2008). We propose to classify weighting schemes based on the categories from the DPSIR framework and on hypotheses of similarity. Challenges from globalization are linked to the capacity to deliver indicators at the level of impact in an international context.

Two different categories of the DPSIR framework, Pressure and Impacts, are applied to define two types of aggregations. The first one, so-called "aggregation – pressure" contains two sub-types using either a similarity of physical units or similarity of potential effects hypothesis. This aggregation can be applied to resource oriented and pollutant-oriented approaches. The second type of aggregation is the so-called "aggregation – impacts" mainly used for pollutant-oriented approaches. It assumes a weighting based on a hypothesis of the similarity of potential damages on some areas of protection like human health or ecosystems (Jolliet *et al.*, 2003).

Pressure categories differ from Impact categories by only describing environmental flows without specifying the exact environmental influence these flows entail. Impact categories attempt to go one step further and describe the specific environmental consequences of certain flows (a process which is inherently uncertain and incomplete, since far from all environmental influences are understood or well quantified). Since some environmental impacts in turn influence the socio-economic system, the impact category may thus provide additional insights on indirect environment-society relations and existing and potential feedbacks. Beyond the fact that several existing aggregations schemes rely on scientifically disputed assumptions, the more they are aggregated down the chain of the DPSIR, the less accurate and less robust the assessments. End-points categories have thus higher levels of uncertainty than the mid-points categories in Life Cycle Impact Assessment (LCIA) (UNEP, 2003).

Some scientific aggregation scheme, such as the aggregation of greenhouse gases effect based on their radiative properties, are available but others are still lacking standardisation (Udo de Haes *et al.*, 2002). Blanc *et al.* (2008) show the interest of applying such a scientific scheme in the case of sustainable environmental indices. Non-scientific weighting schemes are also used based on explicit or implicit societal preferences, for example when using measures of willingness to pay (Reap *et al.*, 2008b), trading off robustness with societal objectives.

The robustness of aggregation in an international context depends on the use of additional information in pollutant-oriented approaches: the availability and quality of data and models for estimating the effective cross-boundary transfer of pollutants through environmental media (air, water and soil) and information on local conditions. Models like EMEP in Europe have shown that a large part of the pollutants deposited in Germany are, for example, of foreign origin (Klein *et al.*, 2007). Only few models are available for modelling the transfer of the large number of existing pollutants and even fewer for the long-range modelling. Damage factors are also scarce outside Europe – and nonexistent for large numbers of widely used substances. (Reap *et al.*, 2008b) review extensively the limitations of life cycle impact assessment among which the selection of impact categories, the data gaps with toxicity-related impact categories or the spatial variations and locations uniqueness.

COMPARISON & NORMALISATION

The "comparison & normalisation" step aims at delivering a performance indicator to inform decision makers of the performance of the synthetic indicator compared to a reference value. References values can be internal, i.e. calculated within the EAM like the sum of impacts or a threshold, or external, e.g. legal limits, targets, or an indicator from another dimension of Sustainable Development. These references have an influence on the overall soundness of the results (exp. 6). Challenges from globalization are related to the change of perspective discussed in section 1, the so-called "local in global" perspective and the way of representing it.

Internal reference values are used in two different ways: for normalizing results in order to compare the performance of different indicators, e.g. in LCA, and for comparing a synthetic indicator to limits computed within an EAM, e.g. in the EF. The validity of the performance indicator is obviously dependent on the validity of the internal reference value, which itself can be based on different data sets and methods than the previously computed synthetic indicator. Internal references values have however the advantage of being submitted to the same scientific validations procedures applied to EAMs, while this is less current for external reference values which are not necessarily resulting from a scientific process. External reference values have the advantage of being not subject to EAM limitations in terms of calculations. Some comparisons with external references value are however clearly not possible due to different system boundaries, resulting in meaningless performance indicators. The use of EAMs in decision-making would clearly gain from further research and guidelines on the choice and soundness of potential internal and external reference values to ensure the soundness and better use of performance indicators.

Reference values are clearly linked to the objectives of an assessment. These objectives are challenged by a global view as mentioned in the first section. From an environmental point of view, a truly international perspective should acknowledge the different environmental profiles of regions. A final indicator should report on the environmental issues that are priorities in each region along a supply chain even if they are not dominant from a global perspective. Normalization should therefore be specific to each region and indicators should report specifically on each of them to know where corrective action is the most needed. None of the approaches surveyed are applying such principle yet and it is unclear that it will be applied since the choice of a reference basis is intimately linked to a policy focus.

MEETING SOCIETAL EXPECTATIONS AND GLOBAL CHALLENGES: AN OVERVIEW FOR SOME EAMS

This section discusses the general fulfilment of expectations by a non-exhaustive list of EAMs and how they cope with the challenges from globalization. An overview of results is presented, classified by outcome, in Table 5. These results complement the first results and issues presented in Table 4 with respect to scale, environmental focus and methodology design.

The list of EAMs presented here differs from the list presented in Table 4. The LCA approach is split into two components: a Life Cycle Inventory (LCI) and Life Cycle Impact Assessment (LCIA). Three versions of the IOA approach are proposed following the discussion in “Allocation – international”: a single country EE-IOA, a partial trade EE-IOA and a full trade EE-IOA.

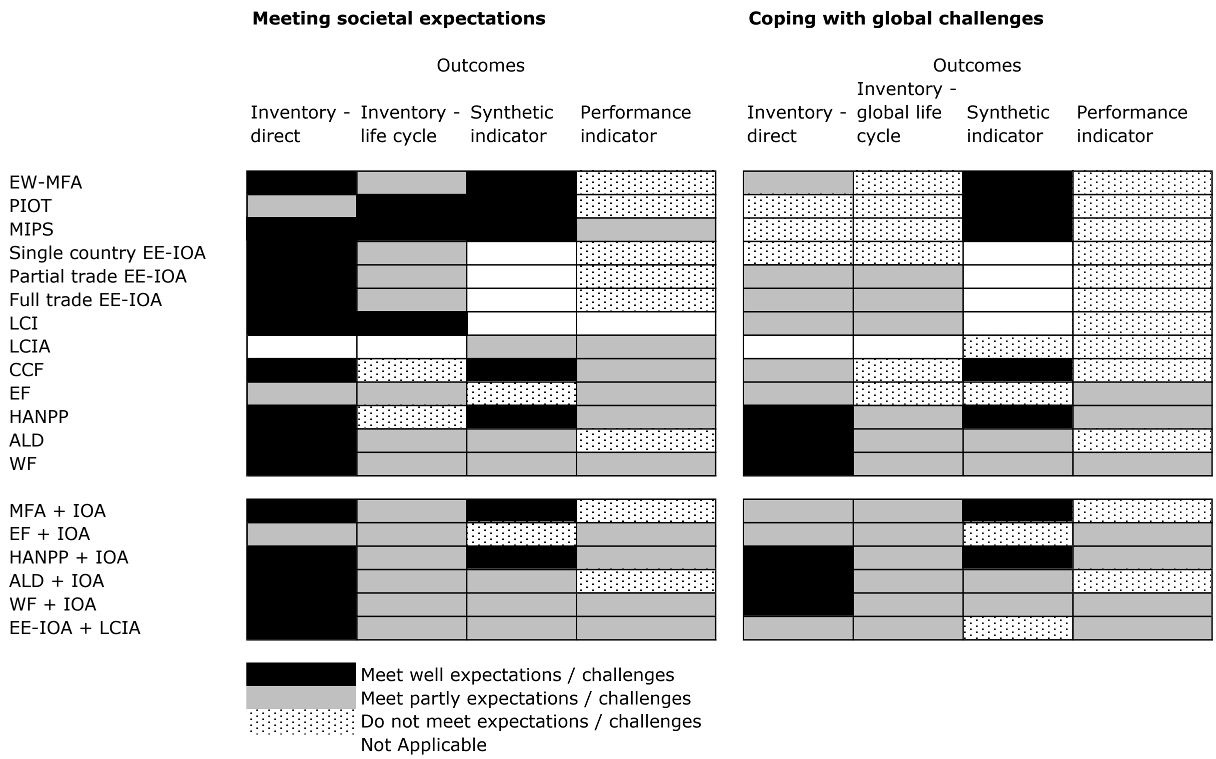

Table 5. General fulfilments of expectations, classified by outcomes, by several EAMs and how the EAMs cope with challenges of globalization.

Table 5 clearly demonstrate a heterogeneous coverage of the outcomes by EAMs and obvious difficulties in meeting expectations and challenges. Existing methodologies are very different from one another and provide, for most of them, only a partial answer to the fairly extensive needs of decision-makers. The largely different levels of satisfaction in meeting expectations and challenges reveal their different orientations, their relatively recent development (for the EF or the ALD), as well as the low cross-fertilization in their developments, each community developing its own tools and own ways of tackling issues. The widespread use of EAMs plays also a role: PIOT and MIPS are not much developed or used. Their capacity to meet the new challenges from globalization appears thus reduced.

The still recent but increasing trend toward the combination of EAMs, called hybridization, encourages exchanges and should help in the achievement of expectations and challenges. This is evidenced in Table 5. The lower part deals with hybrid methods and shows better fulfilment of both expectations and challenges than the upper part dealing with the original methods. For example, EE-IOA + LCIA appears to meet at least partly all societal expectations and all challenges, except for "synthetic indicator".

The main form of hybridization is a combination of EAMs with input-output tables. Five ways of combination have been identified. In the first way, IOA is combined with bottom-up approaches to extend system boundaries and get more detailed results, i.e. in the tiered hybrid analysis, Input-Output based hybrid analysis and integrated hybrid analysis described by Suh & Huppes (2005). In the second way, input-output tables are extended with additional direct environmental requirements, e.g. material or water use, to ease the computation of indicators, to get a life cycle perspective, or to deal with the challenges from globalization. In the third way, already computed indicators are combined with IOA to extend results to additional scales, e.g. to the meso-scale, or to translate results into consumer activities as in the EF approach with Consumption Land Use Matrices (Thomas Wiedmann *et al.*, 2006). In a fourth way, IOA is used to compute conversion coefficients that are later used in the EAM, e.g. indirect material use of products in MFA. In the fifth way, the combination with aggregation methods, like LCIA, aims at generating synthetic indicators from EE-IOA results. An additional benefit from the integration within an input-output framework is the increased comparability of results with socio-economic indicators developed within the System of National Accounts (SNA) (United Nations, 1993). The downside of such practice is however that IOA is subject to large biases because it cannot always adequately represent the underlying physical nature of flows. IOA performs all computations, including allocation, in monetary units and convert results, in a last step, in physical units with the help of environmental factors, for example CO_2 emissions per dollar. The extension of an existing EAM with IOA is thus potentially weakening the robustness of results generally previously based on physical rationales.

The elaboration of a direct inventory is the most common outcome of environmental assessments (Table 5). The system design step is well dealt with by most EAMs but the availability of data is an issue for several of them, even in Europe (MIPS, PIOT, IOA). The transformation of input data is lacking scientific validity in the case of the EF (Piguet *et al.*, 2007). The ALD is assumed adequate but further research is needed since no critical peer review has been identified. Approaches that can be based on GIS data like HANPP and international data sets like the EF have a much better coverage and are more adapted to the challenges of globalization from an inventory view. The EF is however relying also on global factors for product consumption, which are very uncertain and not locally appropriate. While EW-MFA data is already available for a large number of countries, data is lacking for both partial and full trade EE-IOA but large projects such as EXIOPIOL are currently overcoming this limitation (Tukker *et al.*, 2009). The challenge of globalization is also tackled in LCA with the development of regional LCI databases under an international coordination within the UNEP-SETAC life cycle initiative. However development appears to be very slow.

Achieving a global life cycle is a key challenge for EAMs: few methods are able to deliver a life cycle perspective; data and models of international trade are subject to many limitations or simplifications, e.g. trade balances. The elaboration of an inventory with a life cycle perspective is soundly dealt with by approaches like LCI or PIOT while the quality of the IOA is limited by its monetary nature. The macro approaches (EW-MFA, EF, WF and ALD) provide only some rough life cycle perspective, distinguishing at best direct from indirect environmental requirements in aggregates. The HANPP could provide, without difficulty, a rough life cycle perspective, distinguishing direct from upstream flows, but this has not been applied yet. HANPP also includes ways for upstream biomass flows through "embodied HANPP", which includes traded biomass flows and their upstream components. The Corporate Carbon Footprint (CCF) covers direct and indirect emissions from electricity only (scope 2 of the GHG protocol) but other upstream and downward chains are usually not computed or only very roughly (scope 3). The future GHG protocol, currently under elaboration, should provide guidelines to remediate to this issue in 2010. The EF integrates an international view since its inception. Its implementation is however weak since imports are computed with world average factors rather than country-specific ones and trade balance are used. Among the three types of IOA presented, the single country solution is clearly not adapted to an international context but it is nevertheless currently the most used solution. The full trade IOA approach represents the most advanced solution among all EAMs and is, as such, currently the centre of the research focus in this area (Wiedmann *et al.*, 2009).

The quality of the synthetic indicators delivered by EAMs depends on the robustness of the weighting schemes, which are closely related to the stage of the EAM within the DPSIR model. The MIPS, PIOT, EW-MFA, HANPP provide a robust assessment at the level of Pressure. The quality of the EF is however lowered by a lack of a full scientific validation on the energy conversion into the common global hectare unit, since the agricultural EF can be lowered simply by intensification (raising yields). The WF and ALD would benefit from further validations and a more widespread implementation. The quality of the WF and ALD are also lowered because of a lack of scientific validation. The LCIA approach attempts to go beyond Pressure to the Impact level, resulting in indicators more (mid-points like acidification) or less robust (end-points like human-health). Several authors have applied LCIA to resource-oriented approaches extending them to an aggregation based on a similarity of damages. Globalization is a challenge for the approaches adopting a regional perspective. The EF integrates it since its inception but LCIA is still at the beginning of developments for regional impact factors and international transfers of pollutants.

Table 5 clearly establishes that indicators of performance are a weak point of EAMs. Five approaches (EF, ALD, LCIA, HANPP and WF) propose a comparison with internal or external references values but the meaning of the references is not always clear in policy terms. Besides the obvious fact that less resource use and fewer emissions are better, there is rarely a fixed threshold that can be used as a policy goal. However, each of these methods does allow for robust monitoring, thus measuring improvements or worsening in terms of their domain. The multiple indicators provided by LCIA, or a variety of methods, may be more representative of the system's complexity and its tradeoffs, but also reduce the clarity of the message with potentially mixed signals. The lack of scientific validation of the threshold in the EF approach is an important issue. The OECD synthesis report (OECD, 2008b), on material flows mention the need to complement indicators with references values and propose some generic examples. It is not clear, however, that every environmental issue or measure is associated with a clear threshold. EE-IOA indicators and the hybrid approaches based on IOA have a large potential of comparison with other indicators from the SNA but the life cycle perspective is an issue and clear performance indicators are still missing. The potential of comparison of bottom-up studies like LCA is much lower since results are strongly dependant on the system design that is varying between studies. Several initiatives, like (BSI, 2008) are however establishing guidelines for the labelling of products that would allow for such comparison. Globalization is adding specific challenges to all EAMs through the questioning of the objectives underlying the measurement of performances and the relevance of applying the so-called "local in global" view. None of them has dealt with this issue yet.

Provided that the limitations expressed earlier (monetary allocation and approximate modelling of the use of imports) and additional ones are dealt with, the full trade IOA solution, based on Multi-Regional Input-Output (MRIO) models with enough sectors, appears to be an essential part of any solution that will be designed in the future. Firstly, additional research and data development should be performed to deal with issues like the bridge between price and quantities, exchange rates and rapidly changing economic and technology structures. Secondly, the environmental extensions considered should cover issues that are relevant in each region. IOA is however not accurate enough for decision-making at micro and lower-meso-scales where it can only provide a first approximation. It should therefore be complemented by additional bottom-up methodologies, either on an individual basis or through the development of additional hybrid approaches. Such types of hybridization are however still in development stage and require much more work before a potential implementation on a large scale.

The effectiveness of future databases and methodological development in answering these needs and tackling challenges in a cost-effective way could be potentially improved in three ways: *i)* establishing profiles of goods and of regions to better define which data is needed in which context *ii)* optimizing the methodological and data collection effort by concentrating on the few relevant solutions and geo-localized data in each context, rather than aiming at developing catch-all applicable solutions and databases, and *iii)* speeding up the access to adequate EAMs by adopting a modular view of EAMs to take the best solutions in existing methodologies and improve these elements through cross-methodology research groups focusing on specific issues

ANALYTICAL FRAMEWORK FOR EAM ANALYSIS

The work presented so far has established the societal expectations and challenges from globalization faced by EAMs based on what they "are" and what they "do". By exploiting this work as well as the conclusion of the workshop, we are now in a good position to propose a comprehensive analytical framework. This analytical framework is a balanced methodology-policy alternative to the RACER, proposed by the European Commission (European Commission, 2005) and applied by Best *et al*. in (2008) and Lutter and Giljum (2008), which has a strong policy orientation. This framework will permit an objective analysis of the strengths and weaknesses of any EAM with respect to the mentioned issues as well as additional issues related to the use of results in decision-making as recommended by the workshop. The framework is structured along three axes: environmental accounting abilities, decision-making abilities and improvement potential. The first two axes are split into three dimensions, and each dimension provides an answer to specific issues:

Axis #1 Environmental accounting ability

1. Are the inherent qualities of the approach adequate to provide a sound coverage of the environmental issues globally?
2. Is the approach mature and auditable?
3. How are challenges from globalization tackled?

Axis #2 Decision-making ability

4. Is the approach usable?
5. Does the method provide a strong analytical potential?
6. Is the approach compatible or can be integrated with existing systems of indicators?

Axis #3 Improvement potential

7. How could be improved each of the first two dimensions?

Each dimension can be further decomposed into several characteristics, which are presented in Table 6.

Objectives	Dimensions	Issues
Environmental accounting ability	Inherent qualities	Exclusive or best coverage of environmental issues
		Theoretical soundness
		Global life cycle perspective
		Explicit linkage between socio-economic activities and environment
	Maturity and auditability	Overall methodological consistency
		Methodological soundness : - System design - Data preparation - Allocation - Aggregation - Comparison
		Data sets reliability and completeness
		Transparency
	Adaptation to global challenges	Overall methodological consistency
		Methodological soundness : - System design - Data preparation - Allocation - Aggregation - Comparison
		Data sets extension, reliability and completeness
Decision-making ability	Usability	Intelligibility, univocity, acceptance
		Ease of use
	Analytical potential	Causal and structural analysis
	Comparability, compatibility, integration potential	Comparability and compatibility with other indicators (social, economic, environment)
		Compatibility and integration with existing accountings systems, international statistics and other reporting standards
Improvement potential	Improvements in environmental accounting	Inherent qualities
		Maturity and auditability
		Adaptation to global challenges
	Improvements in decision-making	Usability
		Analytical potential
		Comparability, compatibility, integration

Table 6. Analytical framework for EAM analysis

DIMENSION 1: INHERENT QUALITIES OF THE APPROACH

The inherent qualities of the approach are the key expectations that EAMs are facing. The first quality is the capacity to report on environmental issues recognized as important from a scientific perspective. This reporting should provide additional information and insights compared to other EAMs. The second quality is the overall theoretical soundness of the approach, i.e. the scientific validity of the principles underlying the construction of a final indicator as well as their acceptance by the scientific community. The third quality is to adopt a global life cycle perspective, i.e. the capacity to consider the total environmental load of a good or an activity by accounting for the direct and upstream load along the whole production-consumption chains, including its domestic and international parts. The fourth quality is the capacity to provide explicit linkages between the socio-economic activities and their induced environmental flows.

DIMENSION 2: MATURITY AND AUDITABILITY

The ability of EAMs to provide sound indicators over space and time is assessed within the maturity and auditability dimension, without consideration to the globalization challenges. Maturity is defined as the state or quality of being fully grown or developed. A mature EAM is expected to deliver reproducible and accurate results, i.e. in exact correspondence with facts or events. A high degree of maturity implies firstly reliable, complete, and specific data sets covering spatial, temporal or technological peculiarities. It implies then a consistent use, i.e., a homogeneous treatment across methodological steps, of robust methodologies at each of the steps of the workflow. Auditability is defined as the possibility to establish whether a method is functioning properly and, thereafter, that it has worked properly. The requirement for auditability is the transparency of a system and of its internal controls.

DIMENSION 3: ADAPTATION TO GLOBAL CHALLENGES

The ability of EAMs to adapt to global challenges with respect of data and methods is assessed within the dimension “adaptation to global challenges dimension”. As for the faced issues, they are similar to those in the second dimension.

DIMENSION 4: USABILITY

An indicator is of practical use for decision-making if it is intelligible, delivering a clear message and accepted. Definitions are provided in the first section.

DIMENSION 5: ANALYTICAL POTENTIAL

Two outputs of EAMs are mainly used in analyses: final indicators and structural information. Causal analysis, path analysis and structural decomposition are three examples of the analyses, using structural information, that can be applied to identify and quantify the different key factors along a complex cause-effect chain going from the underlying socio-economic driving-forces to the final environmental requirements. These additional insights are crucial to know where to act to reduce the magnitude of environmental issues and to monitor the consequences of actions.

DIMENSION 6: COMPATIBILITY, COMPARABILITY AND INTEGRATION POTENTIAL

The compatibility, comparability and integration potential of EAMs’ assessments with existing indicators and into the basic toolbox of decision-makers requires the compatibility of EAMs with existing legally-binding or voluntary accounting frameworks, norms and standards at national, corporate and products levels. Discussions towards providing integrated accounts have been held for decades at national level and since a few years at corporate level (Jasch & Savage, 2005). All EAMs are however still not considered in these discussions.

DIMENSIONS 7 & 8: IMPROVEMENT POTENTIAL IN ENVIRONMENTAL ACCOUTING AND DECISION-MAKING

The potential for delivering better EAMs can take three forms: perfection, extension or hybridization. Perfection is the improvement of existing data sets, e.g. completing missing values or getting more accurate data and methods. Extension is the development of new data sets and methods. Data sets can be extended to cover missing areas, scales or environmental issues. Methodologies can be extended to e.g., consider specificities of new locations, adequately integrate the consequences of rapid technological changes and flexible production chains (or improve the treatment of trans-boundary issues). Hybridizations are possible by combining methodologies or data sets together. Each of the identified weak points in the other dimensions could be described here if improvement is feasible.

CONCLUSION

EAMs are used by a large number of actors for assessing environmental performances. A fully coherent global multi-scale and multi-criteria picture reflecting societal needs can however not be achieved currently because EAMs are facing un-resolved known problems and have only started dealing with challenges linked to globalization.

We have proposed a description of these challenges based on what EAMs "are", "how" they function and the use of their results in decision-making by the means of an archetypical workflow and an analytical framework. This permits to highlight three current needs. Firstly, the need for additional development with respect to data and methodologies including the combination of these methodologies to foster strengths and reduce weaknesses since all have large limitations. Secondly, the need for a reference framework common to all EAMs enabling comprehensive assessments, based on scientific and societal objectives, to show when and how a specific EAM can be used or should be replaced by others providing similar indicators. Finally, the need for systematic methodological guidelines for all EAMs dealing specifically with identified key issues since environmental accounting is and will remain strongly based on assumptions that need to be accepted and known to users.

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Chapitre 3 : Modèle intégré Economie-Environnement-Impacts

Ce chapitre s'appuie sur une proposition d'article rédigée en anglais et soumise au journal « Nature» par les auteurs suivants : Damien Friot, Shanna Shaked, Gabrielle Antille Gaillard, Suren Erkman, Hy Dao, Sébastien Humbert, Stefan Schwarzer, Julia Steinberger, Lucien Wald et Olivier Jolliet. Nous proposons tout d'abord un résumé étendu de son contenu, qui sera suivi du texte de l'article *in extenso*.

3.1 Résumé étendu

Les chaînes de production-consommation deviennent mondiales. Il en résulte un déplacement d'une partie des émissions et des impacts environnementaux induits par celles-ci, des pays développés, consommateurs, vers les pays en voie de développement, producteurs. La quantification de ces impacts requiert l'utilisation de modèles intégrés qui considèrent les activités économiques de production, de consommation, et d'échanges de biens et services, les émissions qui en découlent ainsi que leur transfert dans l'environnement et le calcul des impacts qui en résultent.

Les modèles économiques mondiaux ont connu un développement important ces dernières années. Ils sont actuellement majoritairement utilisés pour quantifier les émissions de dioxyde de carbone (CO_2) et évaluer divers scénarios quant aux niveaux de concentration des gaz à effets de serre dans l'atmosphère dans les années à venir. Aucun n'est relié à un modèle atmosphérique mondial de transfert de polluants et d'exposition humaine. Pourtant, l'évaluation des impacts sur la santé humaine liés aux polluants locaux et régionaux est cruciale puisque ces impacts représentent les conséquences déjà subies actuellement des modifications des structures de production et d'échange.

Cet article propose un tel couplage entre différents modèles : économie-émissions-transport-exposition-impacts, ce qui représente une avancée en ce qui concerne la modélisation des impacts environnementaux le long des chaînes de valeur. Grâce à ce couplage, nous étudions, pour la première fois à notre connaissance, les impacts sur la santé humaine induits par les particules fines ($PM_{2.5}$) des activités économiques selon une perspective de cycle de vie au niveau mondial. En partant de la consommation dans une région, nous quantifions les activités de production nécessaires dans 19 secteurs différents, selon une perspective cycle de vie, dans chacune des 24 régions géographiques définies dans le modèle ainsi que les émissions induites par ces activités. Suite au calcul du transfert des émissions entre les régions, les concentrations dans l'air sont calculées pour chacune d'entre elles, de même que l'exposition de la population grâce aux cartes de densités de population. Les impacts sur la santé humaine sont ensuite calculés dans chacune des régions du modèle à l'aide de facteurs de dommages générés à partir d'études épidémiologiques publiées.

Nous montrons, tout d'abord, que, pour un grand pays largement ouvert d'un point de vue commercial tel que l'Allemagne, les émissions de particules fines induites par la consommation allemande résultent en des impacts sur la santé humaine qui ont lieu pour les deux-tiers en dehors de l'Europe. Cette proportion est bien plus grande que la part des activités de production (22 %) et la part des dépenses de consommation (5 %) hors d'Europe.

L'extension de cette analyse à l'ensemble des pays du globe, montre qu'un constat similaire peut être effectué pour les autres pays de l'Europe de l'Ouest mais que les impacts induits par les Nord-Américains ainsi que les Japonais et Coréens sont principalement domestiques. Les raisons sont une moins grande ouverture commerciale dans le cas des Etats-Unis et une large exposition de la population au sein des mégapoles japonaises et coréennes. La Chine et l'Asie du Sud sont le lieu de près de la moitié (54 %) des impacts constatés au niveau mondial. Près de 30 % des impacts ayant lieu dans ces régions sont induits par les chaines de production produisant des biens et services pour une consommation étrangère.

Nous montrons ensuite que la délocalisation de la production vers des pays ayant une forte intensité d'impact par dollar de production est actuellement le facteur principal expliquant les impacts liés à la consommation des pays de l'Europe de l'Ouest. La différence en termes de facteur d'émission est la cause principale, celle en termes de densité de population un facteur secondaire.

Nous montrons finalement qu'il n'est pas possible de conclure quant à une exportation volontaire des activités les plus dommageables sur la santé humaine de l'Europe vers les pays en développement. Plusieurs facteurs doivent être pris en compte, comme les efforts importants de réduction des émissions effectués en Europe de l'Ouest, la délocalisation d'un certain nombre d'activités, quelles soient polluantes ou non, ou la tendance à la dématérialisation des économies européennes. Cependant, nous observons une délocalisation apparente des activités les plus dommageables. Les pays de l'OCDE subissent ainsi localement moins d'impacts que ceux qu'ils induisent, de par leur consommation, dans le reste du monde. Le contraire est vrai pour la Chine, l'Asie du Sud et du Sud-est et l'Europe Centrale qui assument par conséquent une part des impacts liés à la consommation des pays de l'OCDE.

Bien que le modèle puisse être amélioré, les résultats sont robustes. L'utilisation de données plus récentes que celles utilisées (2001) augmenterait vraisemblablement encore la part des impacts dans les pays en développement compte tenu de l'augmentation rapide du commerce international ces dernières années.

DELOCALIZATION OF ENVIRONMENTAL IMPACTS ON HUMAN HEALTH DUE TO GLOBAL VALUE CHAINS

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ABSTRACT

Worldwide delocalization of production and the resulting increase in global trade substantially alter emission patterns, shifting emissions from rich consuming countries to manufacturing economies. While the resulting potential carbon leakages have been studied[1], we must also study the human health consequences of the shift of regional pollutant emissions. To address this immediate environmental challenge in developing countries, we need to consistently account for the impacts of regional pollutants by combining i) a life cycle perspective that considers pollutant emissions over the entire global value chain[2] with ii) damage-based modelling of these pollutants accounting for their cross-boundary transfers[3]. We propose the first integrated global model combining an Environmentally Extended Multi-Regional Input-Output model[4] with a pollutant fate, exposure and impact assessment model[3] to describe the full causal chain from consumption, via production, to environmental health impacts. Applying this model to the fine particulate matter ($PM_{2.5}$) emissions associated with the worldwide production of consumer goods, we show that more than 80% of the resulting health impacts induced by the consumption of OECD countries can occur outside their borders, mainly in Asia. The foreign share of these impacts is much larger than what would be predicted by the magnitude of trade and existing assessments of carbon emissions[5]. This difference is mainly due to the large discrepancies in $PM_{2.5}$ emission intensities per dollar of production between producing and consuming regions. Up to 23% of impacts occurring in China and Asia are induced by consumers from other regions. These results show that the current delocalization of production activities increases the global impacts to human health and shifts it to developing economies.

Assessing environmental health impacts induced by consumer goods and services in a globalised world requires accounting consistently for the impacts of current production, consumption and trade patterns along global value chains.

When computing direct and indirect emissions of each good and service over its entire life cycle, double counting must be avoided by complementing the classical territorial perspective used in the Kyoto protocol with additional allocation schemes[1]. Consumption-centered models, such as Environmentally Extended Input-Output[6] (IO) models, can be used to reallocate direct emissions to goods and services within an economy and compute their embodied emissions. IO models have rapidly developed in the last five years, evolving from simplified single-country models with multiple pollutants to multi-country models with partial or full trade linkages[7], thereby substantially improving the robustness of the re-allocation of emissions among goods and countries[8]. Existing multi-region models have so far generally been applied to global emissions such as greenhouse gases. Such applications have demonstrated the inter-country variability of carbon intensities associated with production and have found that, on average, 22% of total CO_2 emissions induced to meet the demand of a country for consumer goods take place outside its borders[9].

Quantifying the immediate environmental consequences of shifts in global value chains, and better evaluating the effects of OECD (Organisation for Economic Co-operation and Development) consumption on developing economies, requires considering emissions of local and regional pollutants and their impact on regional and global health. The inter-country variability in such health impacts is expected to exceed that of carbon emissions due to large disparities in emission control technologies, as well as in the toxicity, mobility and population exposure of emitted pollutants[10]. Pollutant transport models for Europe have shown that trans-boundary transfers are large; for example, as much as 60% of the concentration of primary particulate matter in Germany is due to transport from outside Germany[11].

To date, no global model includes production, trade and consumption, as well as fate, exposure and impacts. The estimation and consistent allocation of environmental health impacts therefore requires the development and integration of an environmentally-extended global model of the economy, including toxic emissions, with a global pollutant impact assessment model.

We developed the first spatially-explicit integrated global model describing the full causal chain from consumption to environmental health impacts (Fig. 1). Starting from the regional consumption of 24 types of goods in 19 regions for 2001 (see Supplementary Tables S1 and S3), the induced economic activities and emissions are computed and re-allocated from producing to consuming regions with a global inter-industry emissions-extended economic model[12]. Using a pollutant fate and exposure model, we then estimate regional pollutant concentrations and human exposure (through inhalation and ingestion), accounting for substance fate in 59 regions and three environmental media (air, water and soil) and for exposure based on urban and rural population distributions. Finally, epidemiology-based damage factors are used to estimate regional health impacts of this intake in disability-adjusted life years (DALYs)[13]. Here, we applied this model to fine particulate matter ($PM_{2.5}$), which are a main cause of environmentally induced impacts on human health[14,15].

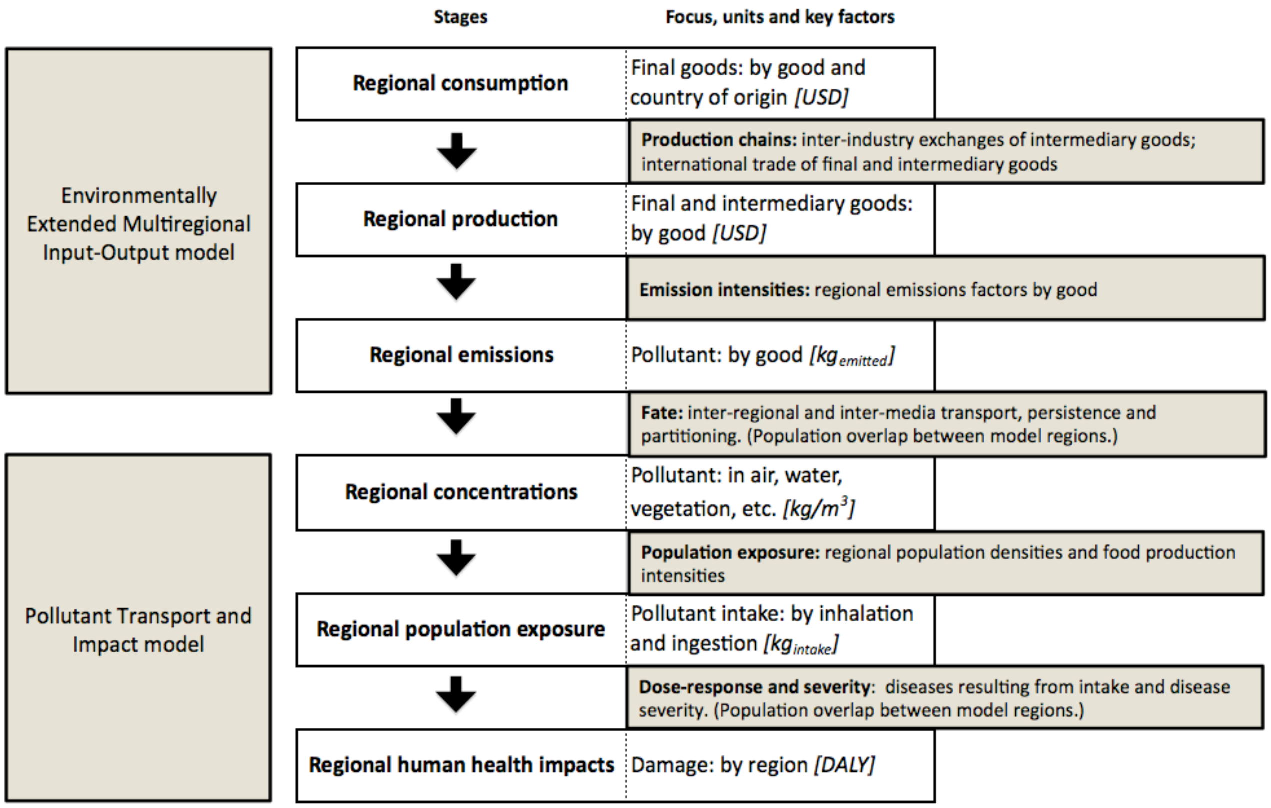

Figure 1 Assessment stages and key factors of the integrated model, combining the Environmentally Extended Multiregional Input-Output model and the Pollutant Transport and Impact model.

We first show that for a large open economy such as Germany, even though few goods and services consumed by households are of foreign origin, 72% of the $PM_{2.5}$ emissions induced by their production occur outside Europe due to the globally-distributed supply chains (Fig. 2). Further accounting for cross-boundary transfers of $PM_{2.5}$ and local exposures results in as much as two thirds of the environmental health impacts occurring outside Europe. More than one third of these impacts occur in China, South Asia, and South East Asia, which receive only 3% of the associated economic activity.

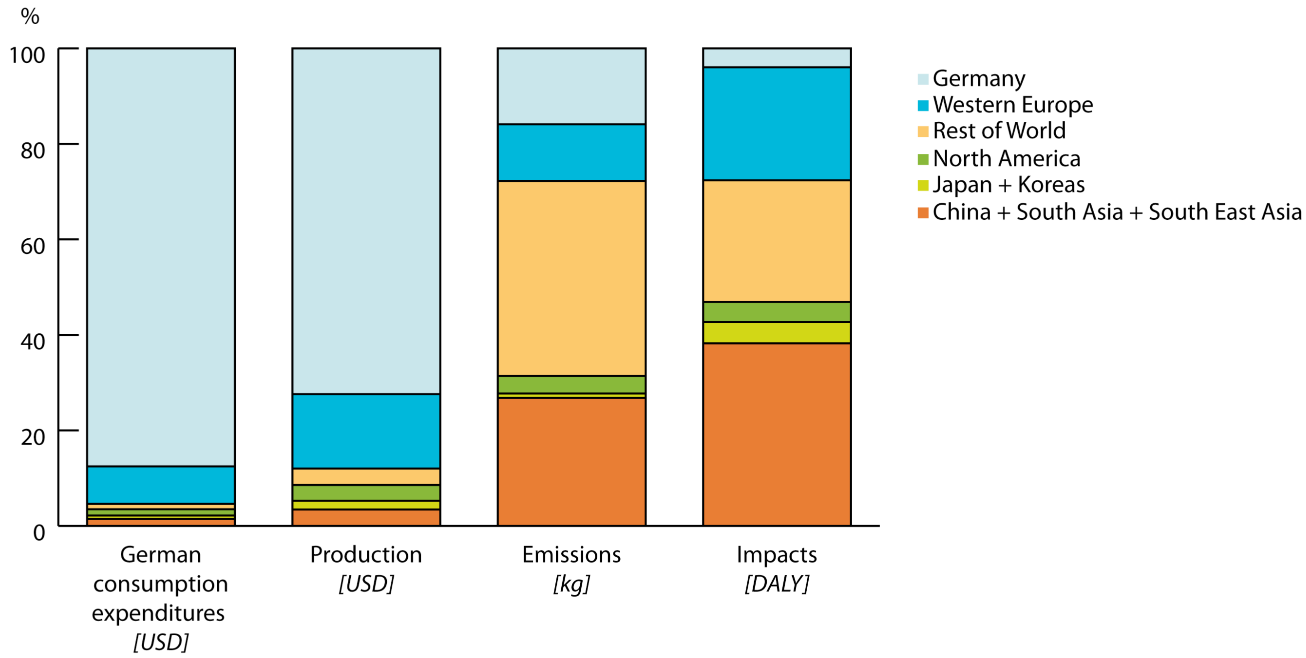

Figure 2 Regional shares of German consumer expenditures, induced production and fine particulate matter ($PM_{2.5}$) emissions and related human health impacts.

Expanding to the consumption of all countries around the globe, we find a similar pattern for Western Europe, as shown in Fig. 3, which contrasts the per capita disparity between (a) induced production, and (b) impacts. As expected, each consumer from North America, Japan and the Koreas, and Europe induces substantially more production than other consumers (Fig. 3a). Impacts from North America and Japan and the Koreas are mostly domestic, due to the US lower openness to trade (19%) and higher emissions intensities, as well as high local exposures of mega-cities in Japan and the Koreas. Due to higher induced economic activity per capita in these regions, impacts are higher than those from Europe, both domestically and in the rest of the world.

Overall, the inhabitants in China and South and South East Asia experience more than half (53%) of the worldwide health impacts due to $PM_{2.5}$ emissions (total orange area in Fig. 3b) despite receiving only 10% of the economic activity (Fig. 3a) induced to meet global consumption. Production for foreign consumers is responsible for 23% of these impacts, with the domestic consumption remaining as the predominant source. On a per capita basis, each North American, Japanese and Korean consumer induces as many impacts in China + South Asia + South East Asia as each local consumer of this grouped region (Fig. 3b).

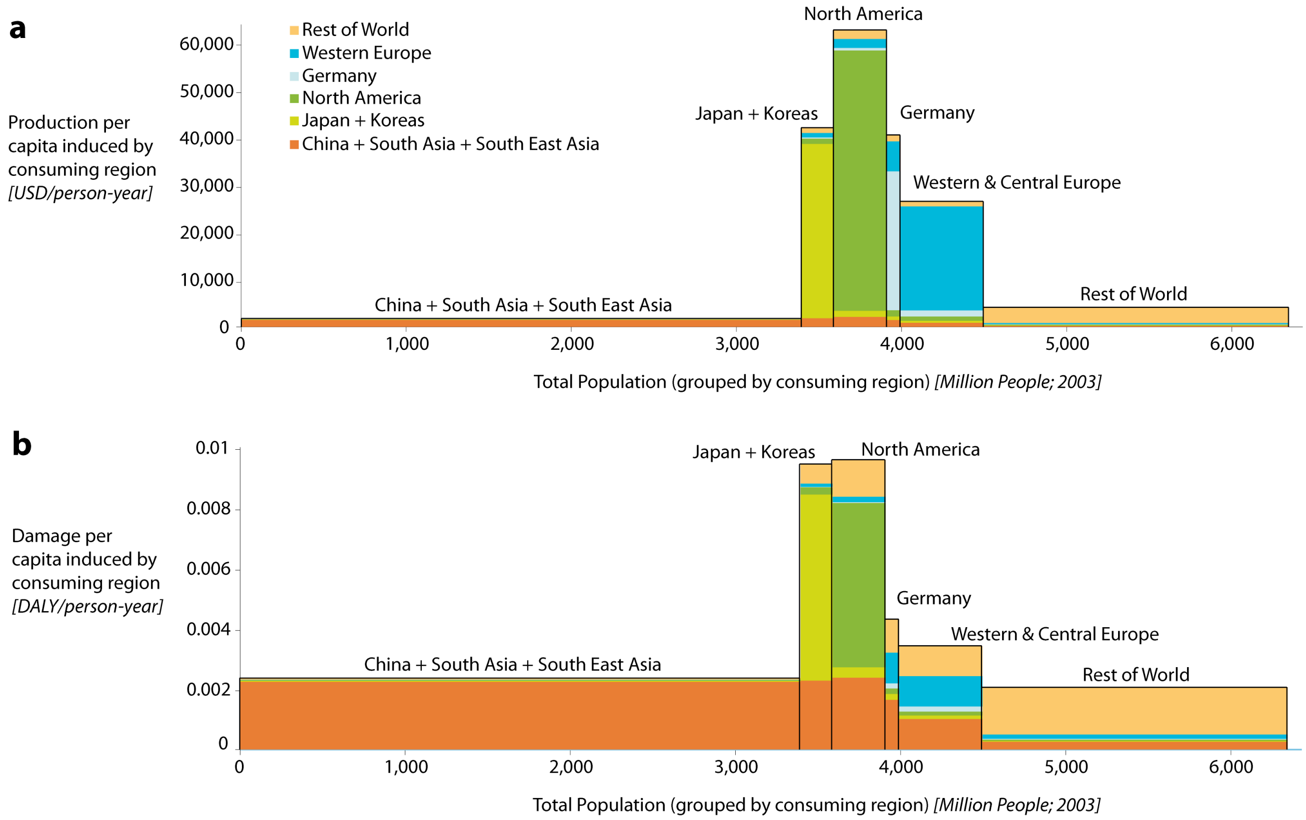

Figure 3 Histogram of annual (a) production per capita (in USD 2001) and (b) impacts of fine particulate matter ($PM_{2.5}$) (in disability adjusted life years - DALYs) per capita induced by each region's consumption. The area of each box represents total induced production (a) or human health impacts (b). Column labels refer to consuming region along x-axis, which induces production and impacts in regions denoted by colour. These six regions are groupings of the 19 regions used in the model (see Supplementary Information Table S1).

The world map in Fig. 4a shows the variation of impact intensities per dollar of production, which is mainly explained by differences in emissions intensities. Accounting for global supply chains, each dollar of production in China results, on average, in 37 times more $PM_{2.5}$ emissions than it would in Germany and 6 times more emissions than in the USA. This reflects the decades-long domestic abatement efforts for Germany, as well as differences in electricity mixes and industrial process efficiencies[16]. In terms of exposure, we found that regional population density plays a limited role in the distribution of impacts, with inhalation dominated by urban exposure in large concentrated urban areas (responsible for 50-98% of regional intake; see Supplementary Information). As a result, delocalizing production from Germany to China or India leads to, on average, 40 (China) to 100 (India) times more impacts to human health per dollar of production.

The current wave of delocalisation of industrial activities to countries with largely fossil fuel-based electricity mixes and low pollution abatement technologies is thus potentially leading to higher global emissions and health impacts. This delocalisation is currently the main factor explaining the health impacts of $PM_{2.5}$ induced by Western European consumption of goods and services.

In Fig. 4, we also show an effective (but not necessarily intentional) export of the most damaging activities to developing countries: the gap between experienced impacts and induced impacts for each region. OECD economies experience lower impacts (negative gap) than what they induce worldwide through their consumption. Central, Eastern and Western Africa (C+E+W Africa), South and South East Asia, and China to a lesser extent assume some of the displaced impacts from the rest of the world's consumption (positive gap), especially from Western Europe, North America, the Arab Peninsula, and Northern Africa.

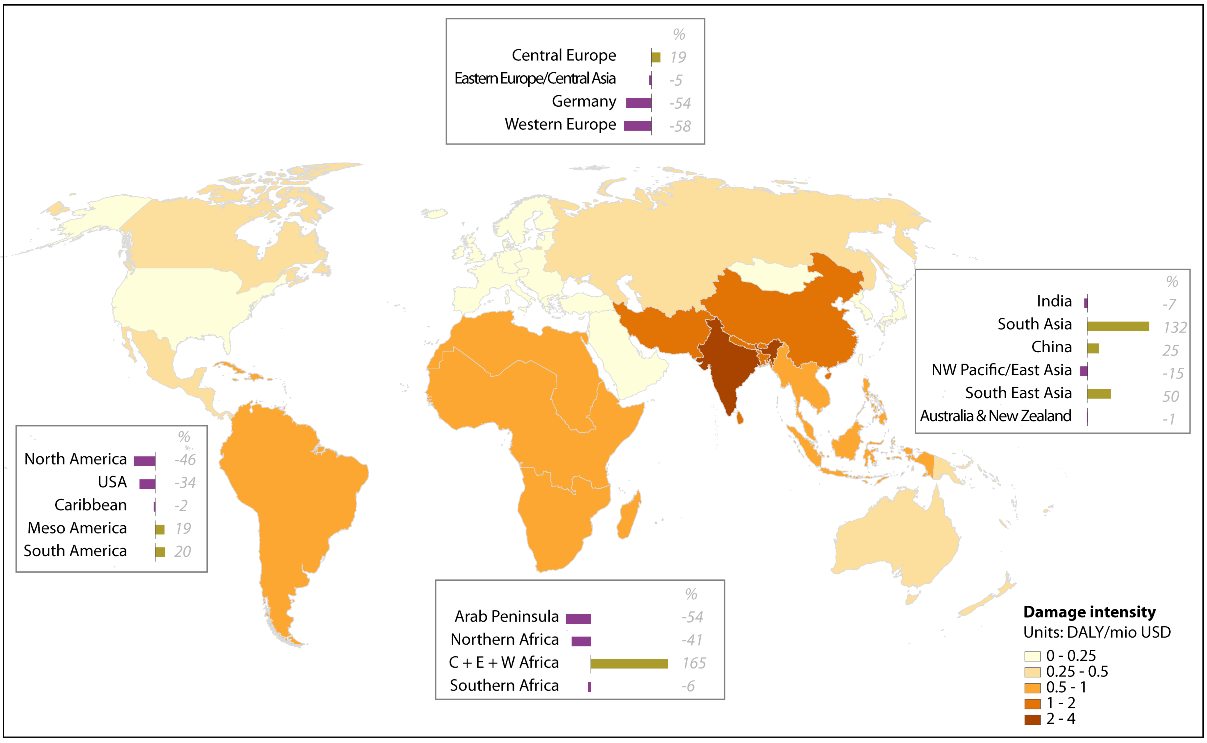

Figure 4 Map of the damage intensity induced worldwide due to regional production [DALY/mio USD] (where DALY is the disability-adjusted life years), with horizontal bars indicating direction and size of damage gap. The damage gap is the difference between experienced damage and induced damage globally through consumption as a fraction of induced damage [($DALY_{exposed}$ - $DALY_{induced\ globally}$) / $DALY_{induced\ globally}$].

A sensitivity study demonstrating the robustness of our model is shown in the Supplementary Information. Methodological improvements should first focus on the refinement of the sector resolution of $PM_{2.5}$ emission factors and the reduction of their uncertainties. This finer resolution would reduce the potential aggregation bias within the model[8]. In general, the data consistency, modelling of imports and sector resolution need to be improved in global IO models[7,17,18]. To improve estimates of pollutant fate and exposure, the spatial resolution should be increased and jet streams should be included to account for long-range transport. We have already performed a first step in this direction by splitting rural and urban exposures. Further work should address additional pollutants, when global inventories are available, and direct emissions by households during the use and disposal phases of products, which are not included here. Finally, indoor emissions throughout the value chain should also be considered due to their potentially large health impacts[19].

We expect that accounting for impacts along global value chains is increasing in relevance every year as long as global trade grows faster than the diffusion of emission control technologies. This delocalisation of impacts increasingly counteracts – indirectly – the domestic abatement policies in OECD countries. This study thus provides confirmation, based on human health impacts of fine particles, of the advantages of adopting a regional or even a global perspective, rather than a national one, when developing pollutant inventories, models and policies. Similarly, it shows that the full global value chain should be considered in assessments of goods, services, companies and countries. This study also suggests to OECD decision makers that the systematic adoption of abatement technologies in Asia and other developing manufacturing countries will substantially reduce impacts due to consumption. Finally, this study provides underlying scientific information for the development of new fair trade schemes, as well as for foreign aid allocation schemes which would thus go beyond donor considerations and consider the needs of recipients[20].

METHODS

The IO[17,21,12] model (19 regions, 24 goods) describes inter-industrial relationships and inter-regional trade at basic prices for 2001. It is based on the widely used global economic database[22] GTAP v. 6. Import matrices are based on trade shares. International transport is specifically considered with three supra-national sectors. The number of sectors reflects the availability of environmental data. We extended the economic model by developing a global inventory of $PM_{2.5}$ by sector, estimating $PM_{2.5}$ with existing national and global inventories and modelled data sets (see Supporting Information). The consumption scenarios include the three components of final demand: household's consumption, government consumption and investment demand.

The global impact assessment model (IMPACT World) extends to a global scale the spatial version of the IMPACT 2002 multimedia model, initially evaluated for Europe[3,23]. It estimates steady state pollutant concentrations and human exposure and intake for continental, oceanic and coastal regions. Within each region, the urban intake fraction[24] is estimated using national urban populations[25] and a database of 1350 cities worldwide[26], and allocating $PM_{2.5}$ emissions between urban and rural areas by population. Trans-boundary transport is simulated by air flows based on annually averaged winds from a global tropospheric chemistry model[27]. Calculated intake fractions correspond well to published intake fractions of available continents (see Supplementary Information Figure S4). Damages to human health (in DALYs) from $PM_{2.5}$ are calculated based on pollutant-specific incidences of resulting diseases from epidemiological studies[15].

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Author Contributions D.F. designed the study, created, ran and evaluated the Input-Output model, analyzed the results, and wrote the paper; S.Shaked created, ran and evaluated the global impact assessment model, analyzed the results, and wrote the paper; G.A. helped on creating the Input-Output model and gave critical feedback in the writing of the paper; S.H. helped create the global impact assessment model, designed the urban exposure calculations and collected urban data, and gave feedback in the writing of the paper; H.D. and S.Schwarzer used GIS to help create the regional divisions in the two models, analyze input data, and help transition between the two models; J.S., S.E. and L.W. gave feedback in the writing of the paper; O.J. helped design the study, helped merge the two models, analyzed the results, and wrote the paper.

Author information Reprints and permissions information is available at www.nature.com/reprints. The authors declare that they have no competing financial interests. Correspondence and requests for materials should be addressed to D.F. (damien.friot@gmail.com).

DELOCALIZATION OF ENVIRONMENTAL IMPACTS ON HUMAN HEALTH DUE TO GLOBAL VALUE CHAINS

SUPPLEMENTARY INFORMATION

1 SUPPLEMENTARY INFORMATION

1.1 REGIONAL DIVISIONS

The regions and region groupings for the environmentally-extended multiregional Input-Output model are presented in Supplementary Table S1. Groupings and names are based on the UN classification[1], with the exception of Israel, which is grouped according to its geographical position (with the Rest of Middle East) and Turkey which is grouped into Central Europe.

6 aggregated regions	19 regions	87 countries and regions from the GTAP database[2]
China + South Asia + South East Asia	China	China, Hong Kong, Taiwan
	India	India
	South East Asia	Indonesia, Malaysia, Philippines, Singapore, Thailand, Vietnam, Rest of Southeast Asia
	Rest of South Asia	Bangladesh, Sri Lanka, Rest of South Asia
Japan + Koreas	Rest of North West Pacific and East Asia	Japan, Korea, Rest of East Asia
North America	Rest of North America	Canada, Rest of North America
	USA	USA
Germany	Germany	Germany
Western and Central Europe	Central Europe	Rest of Europe, Albania, Bulgaria, Croatia, Cyprus, Czech Republic, Hungary, Malta, Poland, Romania, Slovakia, Slovenia, Estonia, Latvia, Lithuania, Turkey
	Rest of Western Europe	Austria, Belgium, Denmark, Finland, France, United Kingdom, Greece, Ireland, Italy, Luxembourg, Netherlands, Portugal, Spain, Sweden, Switzerland, Rest of European Free Trade Association
Rest of World	Arabian Peninsula/Mashriq/Israel	Rest of Middle East
	Northern Africa	Morocco, Tunisia, Rest of North Africa
	Southern Africa	Botswana, South Africa, Rest of South African CU, Malawi, Mozambique, Tanzania, Zambia, Zimbabwe
	Western/Eastern/Central Africa/ Western Indian Ocean	Rest of Southern African Development Community, Madagascar, Uganda, Rest of Sub-Saharan Africa
	Caribbean	Rest of Free Trade Area of the Americas, Rest of the Caribbean
	South America	Colombia, Peru, Venezuela, Rest of Andean Pact, Argentina, Brazil, Chile, Uruguay, Rest of South America
	Meso-America	Central America
	Australia and New Zealand/South Pacific	Australia, New Zealand, Rest of Oceania
	Eastern Europe/ Central Asia	Russian Federation, Rest of Former Soviet Union

Supplementary Table S1 List of regions in multi-regional Input-Output model.

The 17 regions in the pollutant transport and impact model (Supplementary Table S2) are similar to those chosen for the Input-Output model, but with some key differences due to less emphasis on geographical boundaries and more on population densities and meteorological conditions. Because of such considerations, some countries have been split between two regions. 42 additional regions, not presented here, are designed to cover pollutant fate and transport in oceans and coastal areas.

Region ID	Region Name	Countries in each region
W1	**West Asia**	Russian Federation, Afghanistan, Iran (Islamic Republic of), Kazakhstan, Kyrgyzstan, Mongolia, Tajikistan, Turkmenistan, Uzbekistan, Western China
W2	**Indochina**	Brunei Darussalam, Cambodia, Lao People's Democratic Republic, Malaysia, Maldives, Myanmar, Philippines, Singapore, Thailand, Viet Nam, Indonesia
W3	**N Australia**	Australia, Wallis and Futuna Islands
W4	**S Australia+**	Australia, New Zealand
W5	**S Africa+**	Angola, Botswana, Comoros, Lesotho, Madagascar, Malawi, Mauritius, Mozambique, Namibia, Rwanda, Réunion, South Africa, Swaziland, United Republic of Tanzania , Zambia, Zimbabwe, Democratic Republic of the Congo, Congo, Gabon, Kenya, Uganda, Saint Helena, Seychelles
W6	**N Africa+**	Democratic Republic of the Congo, Congo, Gabon, Kenya, Uganda, Algeria, Bahrain, Benin, Burkina Faso, Burundi, Cameroon, Cape Verde, Central African Republic, Chad, Côte d'Ivoire, Djibouti, Egypt, Eritrea, Ethiopia, Gambia, Ghana, Guinea, Guinea-Bissau, Iraq, Israel, Jordan, Kuwait, Lebanon, Liberia, Libyan Arab Jamahiriya, Mali, Mauritania, Morocco, Niger, Nigeria, Oman, Occupied Palestinian Territory, Qatar, Sao Tome and Principe, Saudi Arabia, Senegal, Sierra Leone, Sudan, Syrian Arab Republic, Togo, Tunisia, United Arab Emirates, Western Sahara, Yemen, Equatorial Guinea, Somalia
W7	**Argentina+**	Argentina, Chile, Falkland Islands (Malvinas), Paraguay, Uruguay
W8	**Brazil+**	Bolivia, Peru, most of Brazil, Colombia, southern Ecuador
W9	**C America+**	Anguilla, Antigua and Barbuda, Aruba, Bahamas, Barbados, Belize, Bermuda, British Virgin Islands, Cayman Islands, Costa Rica, Cuba, Dominica, Dominican Republic, El Salvador, French Guiana, Grenada, Guadeloupe, Guatemala, Guyana, Haiti, Honduras, Jamaica, Martinique, Mexico, Montserrat, Netherlands Antilles, Nicaragua, Panama, Puerto Rico, Saint Kitts and Nevis, Saint Lucia, Saint Pierre and Miquelon, Saint Vincent and the Grenadines, Suriname, Trinidad and Tobago, Turks and Caicos Islands, United States Virgin Islands, Venezuela (Bolivarian Republic of), part of Brazil, Colombia, northern Ecuador
W10	**USA+**	Southern Canada, USA (except Alaska)
W11	**Antarctica**	Antarctica
W12	**N Europe + N Canada**	Alaska, Greenland, Iceland, Finland, Northern parts of Canada, Norway, Sweden, Russian Federation
W13	**Europe+**	Gibraltar, Greece, Hungary, Ireland, Italy, Latvia, Liechtenstein, Lithuania, Luxembourg, TFYR Macedonia, Malta, Moldova, Monaco, Netherlands, Poland, Portugal, Romania, San Marino, Serbia, Slovakia, Slovenia, Spain, Switzerland, Turkey, Ukraine, United Kingdom ; Southern parts of Norway, Sweden, Russian Federation
W14	**East Indies**	Indonesia, American Samoa, Cook Islands, Fiji, French Polynesia, Guam, Kiribati, Marshall Islands, Micronesia (Fed. States of), Nauru, New Caledonia, Niue, Northern Mariana Islands, Palau, Papua New Guinea, Samoa, Solomon Islands, Timor-Leste, Tokelau, Tonga, Tuvalu, Vanuatu
IND	**India+**	India, Bangladesh, Bhutan, Nepal, Pakistan, Sri Lanka
CHI	**E China**	Eastern China, Hong Kong SAR
JAP	**Japan+**	Japan, North Korea, South Korea

Supplementary Table S2 List of regions in global transport and impact model.

1.2 COMMODITIES IN THE INPUT-OUTPUT MODEL

The 24 commodities are an aggregation of the commodities from the GTAP database[2] v.6 (Supplementary Table S3).

Commodities of the IO model	GTAP sector names
Rest of crops	Cereal grains nec / Vegetables, fruit, nuts / Oil seeds / Sugar cane, sugar beet / Crops nec
Rice	Paddy rice
Plant-based fibers	Plant-based fibers
Cattle and other animals products	Bovine cattle, sheep and goats, horses / Animal products nec / Raw milk / Wool, silk-worm cocoons
Forestry	Forestry
Fishing products	Fishing
Land transport	Transport nec
Water transport	Water transport
Air transport	Air tranport
Coal	Coal
Crude petroleum	Oil
Gas	Gas
Minerals	Minerals nec / Mineral products nec
Processed food	Bovine meat products / Meat products nec / Vegetable oils and fats / Dairy products / Processed rice / Sugar / Food products nec / Beverages and tobacco products
Textiles and leather	Textiles / Wearing apparel / Leather products
Wood and papers products	Wood products
Petroleum products	Petroleum, coal products
Chemicals	Chemical, rubber, plastic products
Ferrous metals	Ferrous metals
Non-ferrous metals	Metals nec
Other manufactured goods	Metal products / Motor vehicles and parts / Transport equipment nec / Electronic equipment / Machinery and equipment nec / Manufactures nec
Electricity	Electricity
Sales	Trade
Services	Gas manufacture and distribution / Construction / Communication / Financial services nec / Insurance / Business services nec / Recreational and other services / Public Administration, Defense, Education, Health / Dwellings

Supplementary Table S3 List of commodities in the multi-regional Input-Output model.

1.3 SOURCES AND METHODS FOR $PM_{2.5}$ EMISSIONS INVENTORY

The $PM_{2.5}$ global emissions inventory is based on official emissions inventories from the LRTAP[3], NAMEA satellites of the national accounts[4], modelled data from the RAINS[5] model for European regions, national emissions inventories for Canada, USA and Mexico[6], modelled data from the GAINS database for China and India[7], and a modelled inventory for Asia[8]. Emissions for other regions are modeled based on the Mexican inventory, assuming similar emissions factors per dollar of production in Purchasing Power Parity. Emissions from the industry are separated from emissions directly emitted from households based on data from the literature. Emissions are then re-classified from source categories to sectors in two steps. First, a straightforward allocation is done for all emissions except emissions from transport. Transport emissions are re-allocated to all sectors, to include own-transport, replicating the EU NAMEA approach[9], and average European ratios.

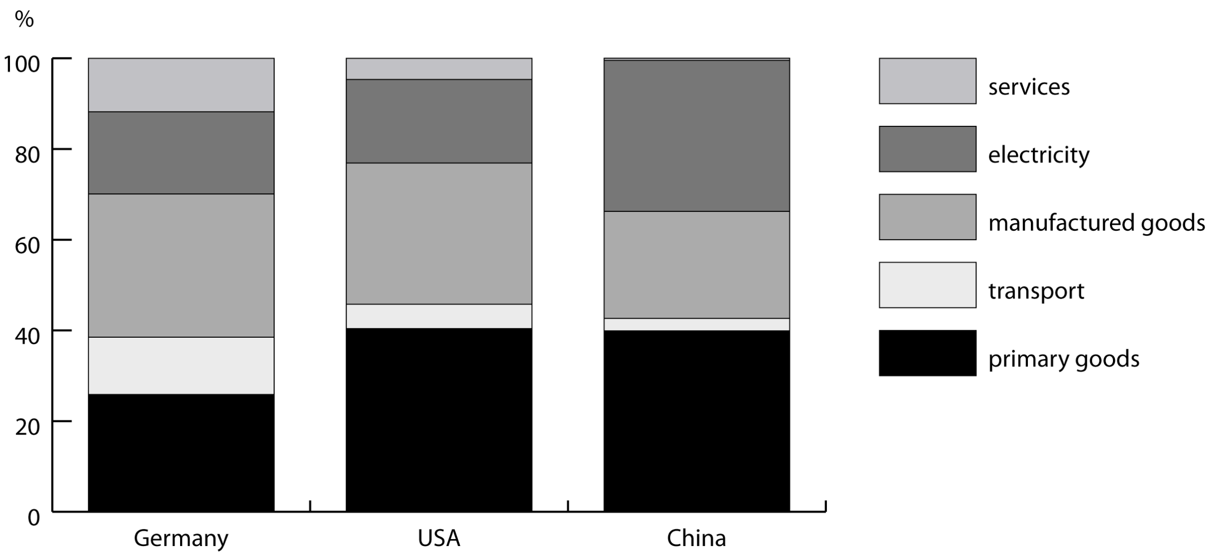
1.4 Exchange rates

Multi-regional Input-Output models require the use of a single currency, in our case the 2001 USD. As is typically done in this type of model, the conversion to USD is based on the market exchange rate[10]. We are aware that a conversion based on Purchasing Power Parity would account for the differences in cost of living between different countries, and thus better represent volumes.

2 Supplementary results

2.1 Distribution of fine particulate emissions from the inventory among commodities

The distribution of fine particulate ($PM_{2.5}$) emissions associated with the different commodities in Germany, USA and China is shown in Supplementary Figure S1. Commodities are grouped into five categories: primary goods, transport, manufactured goods, electricity, services including sales.



Supplementary Figure S1 Distribution of fine particulate emissions associated with different commodities for Germany, USA and China.

2.2 INTAKE FRACTIONS

The intake fraction (iF) is defined as the fraction of pollutant emitted that is eventually taken in by a population[11]. In a simple box model, it is estimated by assuming any emissions immediately diffuse evenly in the box, and using the subsequent concentration and population densities to estimate intake fraction. A recent spatialized study of North America[12] showed that this method can severely underestimate iFs by falsely diluting urban emissions and exposure in the surrounding regional or continental box. The authors find that a key factor determining iFs of urban emissions is the average linear population density of the urban area. Using equation S2 of the study and urban population data (www.demographia.com), we estimate the average intra-urban iF of each region in our global impact assessment model. The emissions weighted average (here estimated as a population weighted average) of the intra-urban iF and continental iF yields an estimated iF for urban emissions ('urban intake fraction'). Key model parameters and these intake fractions are provided in Supplementary Table S4. The stack height of emissions can also play a key role in exposure, but detailed information at the level of this model is not available.

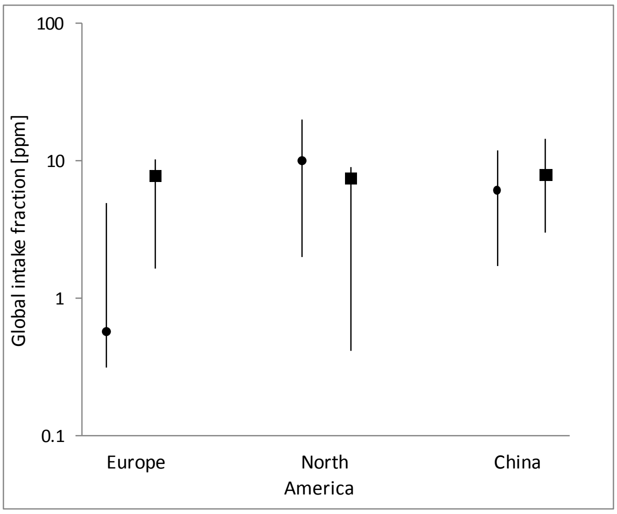
Impact region	**Population** [millions]	**Area** [km^2]	**Urban fraction** [-]	**Urban linear pop. density** [persons/ km]	**Intake fraction - continental emission** [mg_{intake}/ $kg_{emitted\ rural}$]	**Intake fraction - urban emission** [mg_{intake}/ $kg_{emitted\ urban}$]
W1	220	1.69E+13	52%	53,000	1.04	5.97
W2	375	3.26E+12	43%	109,000	1.92	10.12
W3	3	6.58E+12	88%	23,000	0.15	3.71
W4	22	1.54E+12	88%	42,000	0.2	6.51
W5	297	1.01E+13	35%	69,000	0.56	4.77
W6	796	2.42E+13	45%	72,000	0.84	6.52
W7	66	4.19E+12	88%	88,000	0.25	13.54
W8	241	1.08E+13	82%	92,000	0.41	13.42
W9	265	5.93E+12	73%	86,000	0.68	11.57
W10	339	1.45E+13	81%	53,000	0.45	7.46
W11	0	2.79E+13	0%	-	0	0
W12	18	1.83E+13	71%	19,000	0.17	2.56
W13	759	8.57E+12	71%	49,000	1.73	7.84
W14	207	1.96E+12	49%	105,000	1.21	9.98
IND	1,540	4.63E+12	29%	114,000	5.18	11.08
CHI	1,323	6.43E+12	43%	66,000	3.26	8.23
JAP	200	5.98E+11	69%	239,000	2.64	30.01
World[a]	6,671	1.66E+14	49%	82,000	2.49	11.13

[a] first two columns are sums; remaining columns are population-weighted averages based on urban fractions.

Supplementary Table S4 Key parameters and intake fractions for pollutant transport model.

The model framework has been evaluated for a spatial version of Europe[12], but few studies are available to compare with the continental intake fractions presented here. Supplementary Figure S2 shows a comparison of the model's predicted intake fractions with published intake fractions for

Europe, North America and China. The North American and China intake fractions match well, but the European intake fractions calculated here are substantially higher, which may be because the published data are taken from a study that did not explicitly account for urban intake.



Supplementary Figure S2 Global intake fractions (in parts per million, mg inhaled for every kg emitted) for emissions in the regions along the x-axis. Circles represent published values for Europe[13,14], North America[12] and China[15], and squares represent intake fractions estimated by the model presented here. Lines span the minimum and maximum published values and the continental and urban intake fractions for the model presented here.

2.3 REGIONAL VALUES AT SEVERAL STAGES IN THE MODEL, EMISSIONS FACTORS AND OPENESS TO TRADE

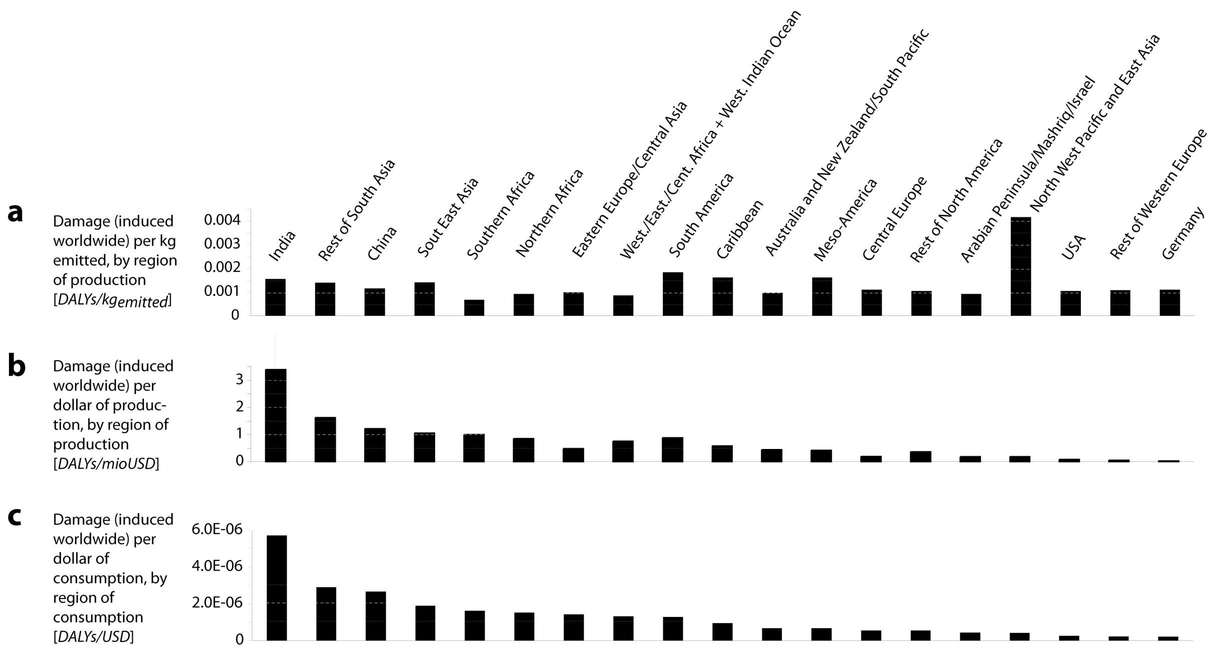
For each stage of the model described in Figure 1, the regional quantities are shown in Supplementary Table S5. Two factors, emissions intensities and openess to trade are also included.

Regions	Regional consumption of final goods [mioUSD]	Regional production [mioUSD]	Average emissions intensities [$kg_{emitted}$/USD]	Openness to trade: (Imports + Exports) / GDP [-]	Regional emissions of $PM_{2.5}$ [$kg_{emitted}$]	Regional population exposure by inhalation [kg_{in}]	Regional health damage experienced [DALY]
Australia and New Zealand/South Pacific	397,814	784,554	4.57E-04	38.1%	3.59E+08	1894	265,141
China	1,467,212	4,117,185	1.06E-03	45.1%	4.35E+09	34967	4,895,425
Rest of North West Pacific and East Asia	4,400,897	8,332,033	4.36E-05	19.9%	3.63E+08	11126	1,557,639
India	465,101	865,165	2.19E-03	21.4%	1.89E+09	17652	2,471,345
South East Asia	550,014	1,338,820	7.53E-04	84.7%	1.01E+09	11161	1,562,564
Rest of South Asia	145,675	257,293	1.17E-03	32.0%	3.01E+08	7008	981,139
Rest of North America	647,953	1,244,080	3.55E-04	60.1%	4.42E+08	2372	332,010
USA	10,431,507	17,933,325	8.23E-05	18.6%	2.95E+09	22841	3,197,776
Meso-America	675,246	1,176,338	2.57E-04	41.2%	3.03E+08	3845	538,261
South America	1,066,864	1,903,826	4.82E-04	23.3%	9.17E+08	11776	1,648,658
Caribbean	152,506	253,860	3.62E-04	48.1%	9.18E+07	1019	142,648
Rest of Western Europe	6,196,628	11,732,302	4.82E-05	31.4%	5.66E+08	4199	587,876
Germany	1,642,581	3,498,763	2.88E-05	54.6%	1.01E+08	1152	161,323
Central Europe	601,536	1,397,372	1.81E-04	67.5%	2.52E+08	2794	391,217
Eastern Europe/Central Asia	364,122	1,414,981	4.86E-04	49.8%	6.88E+08	3548	496,675
Arabian Peninsula/Mashriq/Israel	611,968	1,013,740	2.01E-04	58.7%	2.04E+08	884	123,700
Northern Africa	230,100	459,703	9.29E-04	46.7%	4.27E+08	1475	206,499
Southern Africa	131,898	303,023	1.51E-03	48.2%	4.57E+08	1437	201,203
Western/Eastern/Central Africa/ Western Indian Ocean	173,749	313,032	8.81E-04	64.3%	2.76E+08	4298	601,724

Supplementary Table S5 Annual (2001) regional values at several stages in the model and emissions factors.

2.4 IMPACT INTENSITIES

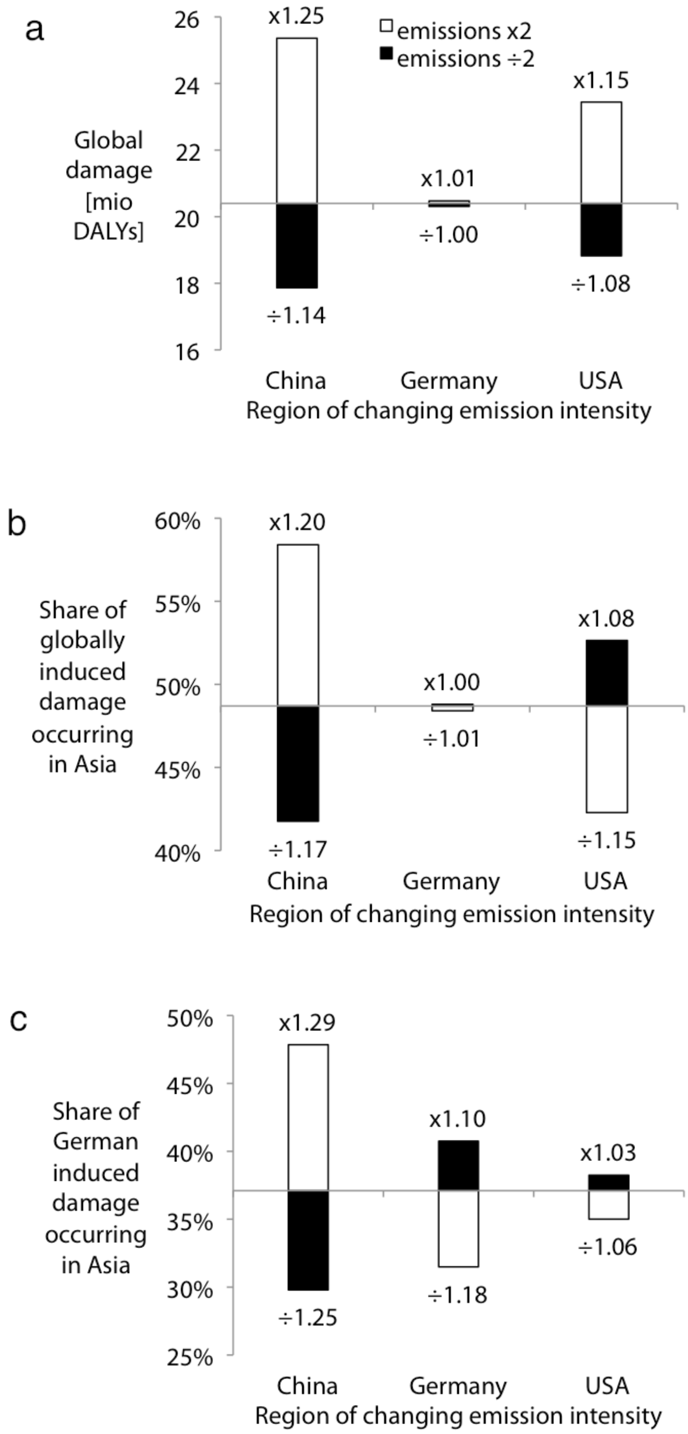
A selection of results showing several impact intensities is proposed in Supplementary Figure S3. The impacts induced worldwide per kilo emitted [DALY/$kg_{emitted}$] in each region are shown in figure S3a. These impacts depend on the population density of the area where fine particulates are deposited following their air transfer. The impacts induced worldwide per dollar of regional production [DALY/USD of production] in each region are shown in S3b. Multiplying these factors with regional emissions of $PM_{2.5}$ from the preceding table provides the impacts induce by each regional production. The values in figure S3b represent global impacts due to local emissions from local production, whereas the values in the map in figure 4 represent global impacts due to emissions from local production as well as from the supply chain needed for that local production (making it is a more comprehensive measure of the impacts of production within a given region). Figure S3c shows the impacts induced worldwide per dollar of consumption [DALY/USD of consumption]. Multiplying these figures with the total consumption of each region provides the sum of impacts induced by the consumption of each region as provided in Figure 3b.



Supplementary Figure S3 Damage factors per kilogram emitted, per dollar of production and per dollar of consumption in each region.

2.5 EVALUATING THE ENVIRONMENTALLY EXTENDED MULTI-REGIONAL INPUT-OUTPUT MODEL

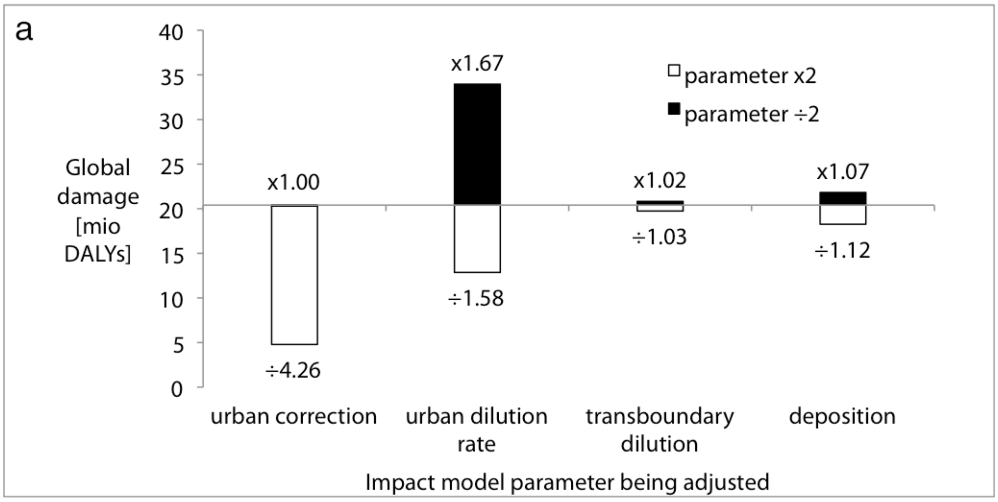
We calculated how sensitive key results are to uncertain input parameters. Taking the input emissions intensities (kg $PM_{2.5}$ emitted per dollar of production) for China, USA and Germany, we multiplied and divided each by two to examine subsequent changes in impacts (Supplementary Figure S4). We focused on changes in the total global impacts, the share of impacts in Asia (China, South Asia and South East Asia) induced by global consumption, and the share of impacts in Asia induced by German consumption. As expected, we found that these indicators are most sensitive to changes in Chinese emissions intensities, followed by changes in US emissions intensities. However, our model results are still relatively robust, since doubling or halving Chinese emissions intensities, leads to less than 30% change in the results presented here.

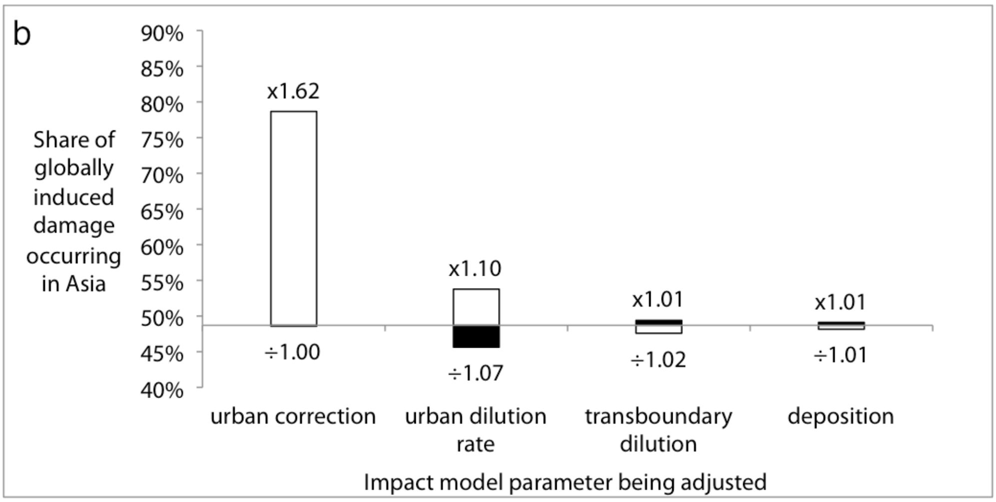


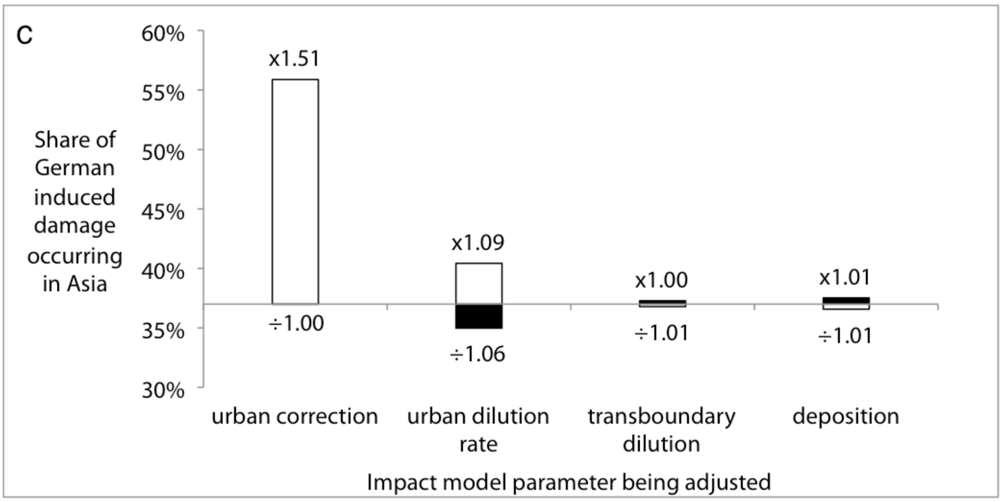
Supplementary Figure S4. Sensitivity studies of various output parameters in the impact model to key input parameters in the multi-regional Input-Output model. Output parameters examined are (a) change in global human health impacts (due to $PM_{2.5}$ emissions to meet global final demand), (b) change in share of global induced impacts occurring in Asia (China, South Asia, and South East Asia), and (c) change in share of German-induced impacts occurring in Asia. Bars represent changes due to multiplying by two (white bars) or dividing by two (black bars) the emissions per dollar for the region *on the x-axis. Factors above positive bars and below negative bars represent, respectively, the factors increase and decrease of the default model value.*

2.6 EVALUATING POLLUTANT TRANSPORT AND IMPACT ASSESSMENT

A sensitivity study was conducted on the dependencies of the pollutant transport and intake model by examining the effects of changing key input parameters (Supplementary Figure S5). As would be expected from the dominance of urban intake on total global intake, we find that the total global health impact strongly depends on urban parameters, but has little dependence on trans-boundary winds and particulate deposition rates. If we assume an average intake fraction in each region based on the average regional population density (as is typically done in global models), rather than separately calculate and then combine the urban and rural intake fractions (as done here), the total global impacts are underestimated by a factor 4 and the Asian shares of impacts are overestimated (bar marked 'urban correction'). The total global health impacts also depend on the assumed urban dilution rate, which is a product of the wind speed and mixing height in urban areas. Here, we use the average urban dilution rate from 75 U.S. urban areas[16], and apply this to all regions due to lack of urban dilution rate data in the rest of the world. Our sensitivity study shows that increasing and decreasing the 'urban dilution rate' by a factor 2 causes an increase and decrease in total impacts of 1.67 and 1.58, respectively, but does not substantially change the Asian share of impacts. Finally we double and halve the 'transboundary dilution' and 'deposition' rates by changing the inter-regional wind speeds and particulate deposition rates, finding that neither has a large effect.







Supplementary Figure S5. Sensitivity studies of various output parameters in the pollutant transport model to key input parameters. Output parameters examined are (a) change in global human health impacts (due to $PM_{2.5}$ emissions to meet global final demand), (b) change in share of global impacts in Asia (China, South Asia, and South East Asia), and (c) change in share of German-induced impacts in Asia. Input parameters listed along the x-axis have been adjusted as follows: 'Urban correction' bars show the change in the output parameter if no urban correction is included in the model, and the other bars represent changes due to halving (black bars) or doubling (white bars) the input parameter on the x-axis. Factors above and below bars represent, respectively, the factors increase and decrease in the original global human health impact.

The sensitivity study confirms what has been suggested by a previous study[12] that the explicit inclusion of urban areas is important when the gridsize is larger than around 100 km. In such a case, it is likely that accounting for the urban archetype is more important than increasing resolution. The sensitivity study also shows that transboundary transport does not greatly influence the final global impacts or share of impacts.

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Chapitre 4 : Modèle économique et outils analytiques

Ce chapitre s'appuie sur une proposition d'article rédigée en anglais et soumise au journal « Ecological Economics» par les auteurs suivants : Damien Friot et Gabrielle Antille Gaillard. Nous proposons tout d'abord un résumé étendu de son contenu, qui sera suivi du texte de l'article in extenso.

4.1 Résumé étendu

La mondialisation influence la manière dont les émissions de carbone et les impacts environnementaux des produits, et des entreprises qui les produisent, sont comptabilisés. Elle influence également la manière dont les objectifs de réduction d'émissions et les politiques sont envisagées dans la période suivant l'application du protocole de Kyoto. Deux questions de recherche, représentatives de cette influence, ont été identifiées. La première concerne la pertinence d'un tarif douanier sur le contenu attaché[1] en carbone des importations aux frontières de l'Europe qui se baserait sur le pays d'origine des biens. La deuxième question concerne la potentielle contribution, par les pays développés, aux coûts de dé-carbonisation de pays tels que la Chine. Quelle pourrait être une clé de répartition se basant sur les émissions induites par chacun des pays en Chine ?

Apporter une réponse à ces questions demande le développement et l'application de modèles capables de représenter une perspective de cycle de vie au niveau mondial, ainsi que de nouvelles solutions analytiques. Nous présentons de manière formelle dans cet article un modèle entrées-sorties intersectoriel multi-régions, désigné ici sous le nom de MRIO selon l'acronyme anglais (multi-regional input-output model). Nous proposons ensuite deux approches analytiques basées sur les spécificités liées à l'aspect international de ce type de modèle. Ces approches sont ensuite appliquées afin de répondre aux deux questions précédemment mentionnées.

Le modèle MRIO proposé se distingue des modèles à une seule région par l'intégration des importations et exportations au sein de la matrice des échanges intermédiaires. Il relie, par conséquent, l'ensemble des secteurs de production au niveau mondial. Ce modèle comprend également un secteur de transport supranational afin de considérer explicitement le transport international. Le modèle proposé est complété par une extension environnementale comprenant les émissions en carbone de

[1] Le contenu attaché en carbone (« embodied carbon content » en anglais) représente les émissions de carbone ayant eu lieu le long de la chaine de production d'un bien.

chacun des secteurs. Résolu de manière classique, c'est-à-dire par inversion matricielle, il permet de calculer la valeur de la production induite, dans chacun des secteurs et chacune des régions, par une demande finale régionale. Il permet également de calculer les émissions de carbone résultant de cette production.

La première approche analytique proposée est une simplification des résultats d'un modèle MRIO se basant sur l'agrégation des secteurs pour chacun des pays du modèle. Il en résulte une matrice pays-pays qui permet d'identifier la distribution des émissions, au niveau mondial, pour les biens finaux, selon leur origine, consommés par les ménages, le gouvernement ou dans un but d'investissement. La deuxième approche, que nous nommons décomposition en flux sous-jacents permet d'effectuer l'analyse des émissions ayant lieu dans un pays donné. Cette approche sépare les flux économiques ayant lieu dans ce pays en huit catégories en fonction de trois critères : la situation géographique des utilisateurs finaux, la nature des biens dans le tableau entrées-sorties (intermédiaires ou finaux) et la nature des chaînes de production (domestiques ou internationales). Cette décomposition permet d'effectuer une analyse structurelle des chaines de production et d'identifier leur importance ainsi que l'importance de leur contribution aux émissions du pays étudié.

Deux versions du modèle ont été réalisées à l'aide de la seule base de données contenant des tableaux entrées-sorties détaillés au niveau mondial, dénommée GTAP. Une version à 19 régions et 24 secteurs, permettant une vision mondiale synthétique, et une version exploitant le potentiel géographique maximal de GTAP comprenant 87 régions et 24 secteurs. Ces réalisations ont demandé diverses étapes comme la décomposition des prix aux importations pour obtenir un modèle aux prix de base, l'établissement de matrices d'importations par pays ou encore la séparation des secteurs de transports domestiques et internationaux.

L'application de la première version du modèle montre que les émissions de carbone induites par la consommation de l'Allemagne, de l'Europe de l'Ouest, de l'Europe Centrale, de la Chine, des Etats-Unis et du reste du monde sont principalement domestiques dans toutes les régions. Les proportions diffèrent cependant largement. Environ un tiers des émissions induites, par exemple, par l'Allemagne et l'Europe de l'Ouest le sont à l'étranger tandis que les émissions étrangères correspondent à environ 15 % des émissions induites par les Etats-Unis ou la Chine.

Nous montrons, par l'application de la première approche analytique, que pour les biens finaux consommés en Allemagne, la part du contenu attaché en carbone qui est émise dans un autre pays que le pays d'origine des biens oscille entre 11 % et 38 % selon le pays d'origine. Un tarif basé sur le pays d’origine des biens est, par conséquent, potentiellement inadéquat dans le cas où le profile carbone du pays d’origine est largement différent de celui des pays en amont des chaînes de production des biens importés. L’application d’un tel tarif demande, par conséquent, une évaluation plus précise du contenu en carbone attaché des biens. Les modèles entrées-sorties peuvent y contribuer mais leur haut niveau d’agrégation ne permet pas une évaluation fine au niveau de chaque bien. Ils devraient ainsi être complétés par des approches de type analyse de cycle de vie par processus.

L’application de la décomposition en flux sous-jacents aux émissions chinoises nous permet d’identifier les chaînes de production responsables de ces émissions. Ces émissions sont majoritairement (à 70 %) induites pour satisfaire la consommation domestique chinoise en biens et services. Ces biens et services sont produits dans des chaines de production quasiment exclusivement domestiques. Les émissions chinoises émises pour satisfaire une consommation étrangère représentent 30 % des émissions chinoises. La consommation américaine est la principale cause étrangère des émissions chinoises, représentant presque 10 % des émissions chinoises. A titre de comparaison, ces émissions sont équivalentes à un tiers des émissions d’origine économique émises en Europe de l’Ouest. Nous retrouvons, en termes d’émissions, le constat qui peut être fait sur le rôle de la Chine au sein des chaînes de production mondiales, c’est à dire son rôle d’atelier. Les émissions liées aux consommations étrangères sont ainsi principalement induites pour la production de biens intermédiaires qui sont exportés et intégrés dans la production de biens finaux dans un autre pays. C’est ce que nous nommons le commerce triangulaire, qui est responsable de plus de la moitié (17 %) des émissions liées aux consommations étrangères. Ces émissions ont la particularité de ne pouvoir être capturées par un tarif basé sur le pays d’origine. La majeure partie des émissions chinoises induites par une consommation étrangère échapperait, par conséquent, à un tel tarif. D’un point de vue d’un tarif concernant les exportations vers l’Europe, ce sont environ 5 % des émissions induites en Chine qui ne seraient pas considérées par un tel schéma.

L’application de la décomposition en flux sous-jacents à la seconde version du modèle permet d’obtenir une vision plus fine des flux responsables des émissions chinoises. En nous basant sur deux hypothèses, nous évaluons quelle pourrait être une clé de répartition des coûts de dé-carbonisation chinois. La première hypothèse est que les contributions sont estimées sur la base des émissions induites en Chine par chacun des pays lors de la production des biens et services destinés à satisfaire la consommation de leurs résidents. La deuxième hypothèse est que seul les pays membre de l’annexe II du protocole de Kyoto sont considérés comme contributeurs potentiels. Ces pays sont ceux qui, dans le cadre du protocole de Kyoto, peuvent aider à réaliser des projets de réduction des émissions dans les États dits à économie en transition. Ces pays induisent environ 78 % des émissions chinoises dues aux consommations étrangères. Dans ce cas de figure, les six contributeurs que sont, par ordre d'importance, les Etats-Unis, le Japon, l'Allemagne, le Royaume-Uni, la France et le Canada, assumeraient plus de 80 % des coûts de dé-carbonisation de la Chine. La comparaison de cette clé de répartition, basée sur les émissions induites en Chine, avec une clé de répartition basée sur les émissions directes reportées dans le cadre du protocole de Kyoto montre de grandes similarités. Dans ce dernier cas, dans lequel les émissions directes des pays seraient appliquées comme base pour une clé de répartition, c'est à dire sans référence aucune à la Chine ni aux liens commerciaux, la contribution du Japon serait cependant fortement diminuée, tandis que les contributions américaines et canadiennes seraient plus importantes. La part des émissions des pays européens serait, elle, presque identique.

EU CARBON TARIFFS & SHARING SCHEME OF THE CHINESE DE-CARBONISATION COSTS: A STRUCTURAL ANALYSIS BASED ON MULTI-REGIONAL INPUT-OUTPUT MODELS

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INTRODUCTION

Globalization is impacting the way carbon emissions and environmental impacts of products, and companies producing, them are accounted for as well as the way carbon reduction targets and policies are envisioned in the post-Kyoto era.

Production-consumption chains are spread on a global scale due to dynamics of relocation (offshoring) and reorganization (outsourcing) of activities (Abonyi, 2006). Part of the South to North pattern of trade is thus transformed from mining and agricultural products against manufactured products to two-ways trade in manufactured products. This is illustrated by the case of China: 80 % of Chinese exports are manufactured products in 2003 (WTO, 2006). This switch from inter-industrial trade, i.e. the classical wine for cloth trade to intra-industrial trade and what Grossman and Rossi-Hansberg (2006) call “task trade”, means that the share of triangular trade flows is increasing between countries having very different production structures, energy sources, technologies and local environmental conditions. Electronics exports of China are, for example, assemblies of components imported from Korea or Taiwan at 60 % which are re-exported after assemblage to Asia (40 %) or the rest of the world (HSBC Global Research, 2004). This switch also means that the share of several developing countries in international trade is growing as a result of their specialization as world factories. China is now getting a major share (6 %) of world exports (2006), and is one of the new key players in international trade.

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Accounting for emissions and impacts in an era of economic globalization requires recognizing local, or at least regional, specificities and thus developing new differentiated datasets. Beyond data collection and processing, environmental accounting also requires the development and adoption of advanced models due to the recent but large adoption of a life cycle perspective in environmental reporting standards in policies, businesses and products. Both the Integrated Product Policy in the EU (European Commission, 2003), the GHG protocol (WRI & WBCSD, 2004) for companies or the PAS2050 for products (BSI, 2008) are thus requiring computing total emissions, adding upstream (supply chain) and downstream (use and end of life) emissions to direct emissions. Modeling schemes like Multi-Regional-Input-Output (MRIO) models are able to deal with this strong constraint of representing a life cycle perspective along global supply chains, a so-called "global life cycle perspective". They are thus currently gaining momentum both in the research (Tukker *et al.*, 2009) and for policy (Tukker *et al.*, 2006).

Responsibilities in carbon reduction targets and policies are also influenced by globalization, as shown by the new proposals coming on the forefront of political agendas from leading economic powers like China or France. While a global thinking was already considered in the Kyoto protocol with respect of co-opted emissions targets, new developments reinforce this trend in the ongoing discussions (Copenhagen Climate Conference): China, the second largest carbon emitter (IEA, 2006) is suggesting that developed nations should bear part of the costs of its own de-carbonization (Anderlini, 2009). This globalization of costs can also be perceived in the French proposal to implement unilateral policies with a global reach: to tax European imports coming from countries with lower environmental standards than the EU to protect it from environmental dumping (Faujas, 2009). These carbon tariffs should discourage the consumption of goods from these areas, inducing them to implement higher environmental standards. The legality and use of these tariffs has been largely discussed (Weber & Peters, 2009; World Bank, 2007). The first joint report on the connections between trade and climate change, by the United Nations Environment Program and the World Trade Organization (2009), concluded that some border tax adjustments would be acceptable.

These two new developments lead to two research questions:

- What could be the sharing scheme of the Chinese de-carbonisation between nations? How could the contribution of the different countries be quantified with respect of the pollution they induce in China?
- Are carbon tariffs based on the country of origin of imports representative of the carbon emissions required for producing these goods? Are these tariffs able to influence countries towards reductions in carbon emissions as expected considering the current structure of international trade?

We propose, in this paper, two complementary analyses of MRIO models that will be applied, in a second step, to these questions.

The first analysis is based on a segmentation of the sector-aggregated matrix of results from a MRIO analysis. This segmentation provides a synthetic view of the magnitude and location of emissions induced by a country final demand, e.g. households consumption, accounting for all emissions induced worldwide for consumed products and services, including traded goods and their supply chains. This analysis also provides basic structural information on the production chains involved to satisfy this final demand and is, as such, a good introduction to the second analysis.

The second analysis is called “underlying-flows decomposition”. It exploits the multi-region and multi-sector nature of MRIO models to provide an analytical view of the structure of the flows inducing emissions within a country. This analysis can be applied to provide a reverse perspective compared to the previous analysis: the identification of the countries inducing emissions within a specific country through their consumption according to a life cycle perspective.

The first question on the sharing scheme of de-carbonisation costs in China based on the economic role of foreign countries can be approached in several ways. A first estimation by an international economist would probably be to consider the direct emissions of exports only and to allocate them to the importing countries. This solution is however unsatisfying for two reasons. Firstly, it does not include backward linkages, i.e. upstream production chains, in China and such coverage of emissions is thus incomplete. Secondly, due to the role of China in production chains, many exported goods are components that will be integrated into other goods possibly consumed in a third country: forward linkages are not considered and the allocation of emissions to the importing economy is thus not really defendable.

A better answer would be to account for these linkages with a MRIO model and to apply the underlying-flow decomposition. The contribution of any country can be computed by looking at the total emissions it induces in China to satisfy its final demand over an overall figure representing Chinese emissions. The emissions induced for the satisfaction of final demand means that all emissions, including supply chains emissions, to produce the goods consumed by households, government as well as for investment are accounted for (Suh, 2009).

The second question on the representativity of tariffs can be approached in two complementary ways, a focus on imported goods or on countries of origin. Firstly, the embodied carbon content, i.e. the carbon emitted along the supply chain, of each of the EU imports can be computed by region of emission with a MRIO model. Tariffs based on countries of origin could be relevant if a substantial share of the average embodied carbon is emitted in the country of origin of goods. The approach based on the sector-aggregated matrix can be used to compute this share for consumer goods. Secondly, the share of emissions induced by triangular trade can be computed with the underlying-flows decomposition. We define these emissions from triangular trade, in the case of the EU, as the emissions that are induced in a non-EU country to produce intermediary goods that will be used for the production, in another non-EU country, of final goods consumed in the EU. Such emissions cannot be captured by a EU tariff scheme focusing on the country of origin only since they occur for the production of goods traded between two non-EU trade partners. Their magnitude is thus an indication of the inability of such a tariff scheme to capture a large share of emissions induced by the EU in the rest of the world.

In this work, we use two versions of a world MRIO model extended with emissions for the year 2001. The first one has 19 regions (single or aggregated countries), 24 (+1 supranational trade) sectors and has been developed to track environmental impacts due to criteria pollutants and fine particulates accounting for global production chains in the TREI-C[2] project. The second one is a disaggregated version of this model (87 regions) extended with carbon emissions only.

The remainder of this section describes briefly why MRIO models have been chosen to answer these questions that are based on the following requirements: an assessment of countries and goods

[2] TREI-C: Tracking environmental impacts of consumption: Linking OECD and developing countries for risk analysis and related pressure's alleviation. (www.trei-c.org)

with a life cycle perspective on a global scale. The need for a life cycle perspective disqualifies most of existing models, including world economic models like Computable General Equilibrium models (Dervis *et al.*, 1982) or econometric models, e.g. of the INFORUM type (Almond, 2003; Meyer *et al.*, 2003): they are not able to allocate emissions among the different elements of an international supply chain. The need for a global reach makes difficult the use of bottom-up approaches like Process Life Cycle Analysis (LCA) even if they provide a life cycle perspective (Chambers *et al.*, 2000).

Several types of environmentally extended Input-Output (IO) models have been developed so far. Single country IO models have been largely used for assessing the environmental impacts of domestic consumption patterns, e.g. in Australia (Lenzen, 1998), Denmark (Munksgaard *et al.*, 2000), Sweden (Bergstedt *et al.*, 1999), Switzerland (Kaenzig & Jolliet, 2006) or in Europe (Tukker *et al.*, 2006). These models do not model adequately emissions due to imports as they assume production, technology and emissions structures identical to national ones (Tukker *et al.*, 2009). They therefore do not account adequately for the wide differences in terms of emissions coefficients between countries, e.g. due to different energy sources and end-of-pipe technologies. As shown by (Peters & Hertwich, 2006) for Norway, this perspective is however not enough since a large part of emissions due to national consumption occurs outside the national borders, especially for small open economies and these emissions should be modeled adequately.

Multi-country models have been elaborated with simplifications to go beyond these limitations while keeping data needs low, providing an approximation that is adequate in some cases. Ahmad and Wyckoff (2003) and Machado *et al.* (2001) use model with trade balances or partial trade linkages. In this approach, the full exchanges between trade partners of the country under study are not considered. This practice is supported by (Lenzen *et al.*, 2004), advocating that fully accounting for multilateral trade only slightly affect results. Few MRIO models have been developed in the last few years, providing these full linkages (Friot & Antille Gailllard, 2007; Nijdam *et al.*, 2005; Peters, 2007). We advocate here that this full accounting is required to answer to questions related to the contribution of a country into the emissions of another one and to questions related to the position of a country into international production chains because one-country and multi-country IO models with partial trade linkages cannot consider triangular trade flows. We follow here (Tukker *et al.*, 2009; Wiedmann *et al.*, 2007) who review the different types of IO models and advocate for MRIO models with full trade linkages.

The paper is structured as follow: the MRIO model used as a basis for the two decompositions and its resolution is formally described in section one. The sector-aggregated approach and underlying-flows decomposition are then described in section two. In section three, the method and data sources used for building the TREI-C MRIO model are briefly described. The two analyses are applied in section four and answers to the research questions are proposed. Section five contains a discussion on the proposed analyses and the conclusions.

DESCRIPTION OF THE TREI-C MRIO MODEL

The TREI-C Multi-Regional-Input-Output model is a generalized Input-Output model describing inter-industrial relationships and emissions of pollutants on a world scale. It integrates the full production, trade and consumption linkages between sectors and countries, following the IRIO (Interregional Input-Output) philosophy (Miller & Blair, 1985). This model can be described as an allocation mechanism able to implement a global life cycle perspective: any emission within the system can be re-allocated along global production chains accounting for multiple feedbacks between countries.

An aggregated version of the model with three regions (A, B, rest of the World), one supranational transport sector (TR) and one pollutant is presented in Table 1. Each region can contain one or more sectors. Capital letters are matrices and small letters are vectors.

		Intermediate demand				Final demand			Total output	CO_2
		A	B	W	T	Y_A	Y_B	Y_W		
Intermediate demand	A	Z^{AA}	Z^{AB}	Z^{AW}	z^{AT}	Y^{AA}	Y^{AB}	Y^{AW}	x^A	p^A
	B	Z^{BA}	Z^{BB}	Z^{BW}	z^{BT}	Y^{BA}	Y^{BB}	Y^{BW}	x^B	p^B
	W	Z^{WA}	Z^{WB}	Z^{WW}	z^{WT}	Y^{WA}	Y^{WB}	Y^{WC}	x^W	p^W
	T	z^{TA}	z^{TB}	z^{TW}	z^{TT}	Y^{TA}	Y^{TB}	Y^{TW}	x^T	p^T
EX tax		T^{xA}	T^{xB}	T^{xW}						
IM tax		T^{mA}	T^{mW}	T^{mW}						
Primary inputs		R^A	R^B	R^W	R^T					
Total input		x^A	x^B	x^W	x^T					

A, B, W: 3 countries
T: Supranational transport sector
Z^{dd}: Domestic table, d = A, B, W
Z^{de}: Export table for intermediary goods and services from region d to region e, e = A, B, W
z^{Td}: International transport services sold to country d
z^{dT}: Intermediate inputs sold by country d to the international transport sector
$Z_{(3n+1),(3n+1)}$: Inter-industry, Inter-regional flows of goods.
T^{xe}: Export taxes for imported inputs of country e
T^{me}: Import taxes for imported inputs of country e
R^d: Primary inputs in country d
x^d: Total output from region d
p^d: Emissions from region d
y^{de}: Final demand in region e for the goods of region d
y^{Td}: International transport services sold to country d in the final demand

Table 1 TREI-C Multi-Regional Input-Output table, extended with CO2 emissions.

Compared to a one-region Input-Output model, the TREI-C MRIO model is characterized by the split of exports into two categories (intermediary inputs and final demand). Exports to foreign sectors (Z^{de}) (usually part of final demand) are integrated into the intermediate matrix. Note that Z^{de} can also be interpreted as imports by country e from country d. Final demand for goods of country d ($y^{d\cdot}$) is split into local (y^{dd}) and foreign final demands (y^{de}). Each final demand vector is the sum of households, government and investment demands.

The model differs from a sub-national MRIO model by a specific treatment of prices and international transport. A supranational transport sector has been specified as a separate entity to (a) specifically model international transport, and (b) comply with UNFCCC emissions repertories accounting separately for international marine bunkers and international civil aviation (United

Nations, 2004). Such approach is therefore particularly relevant for dealing with environmental issues. This supranational entity is composed of three sectors, namely land, water and air transport sectors. Each element of the column *T* represents the sales of a sector to the supranational transport entity (Table 1), while the row *T* represents the international transport margins. The model is at basic prices to be solvable: national and international transport margins, as well as trade taxes are specified separately from the price of goods.

The TREI-C MRIO intermediary matrix combines both domestic (main diagonal) matrices and import matrices (from a specific country or from the supranational transport sector) covering all intermediary exchanges. It is a square matrix and the model can be solved in the classical way (Leontief, 1936). Trade (import and export) taxes are not considered in the computation of the inverse. This is a classical feature of the Input-Output framework that is not an issue for the international allocation.

The basic equation of the Input-Output model becomes, for country *A*:

$$x^A = (Z^{AA} + Z^{AB} + Z^{AW})i + z^{AT} + y^{AA} + y^{AB} + y^{AW} \tag{1}$$

where the notations are given in Table 1. The first and fifth elements are domestic sales, elements 2 and 3 (6 and 7) are exports to foreign sectors, respectively final demand, while element 4 is sales to the supranational transport sector.

The input coefficient matrix *A* is:

$$A = Z\hat{x}^{-1} \tag{2}$$

The matrix *A* is composed of four different types of coefficients. The domestic input coefficients are on the diagonal, i.e. like in classical Input-Output models, where subscripts *i*, *j* are sectors *i* and *j*:

$$a_{ij}^{dd} = \frac{z_{ij}^{dd}}{x_j^d}, d = A,B,W \tag{3}$$

If x_j^e is the output of the receiving country, the interregional trade coefficients are:

$$a_{ij}^{de} = \frac{z_{ij}^{de}}{x_j^e}, d = A,B,W \ \& \ e = A,B,W \ \& \ e \neq d \tag{4}$$

The supranational transport coefficients are:

$$a_i^{dT} = \frac{z_i^{dT}}{x^T}, a_j^{Td} = \frac{z_j^{Td}}{x_j^d} \,\&\, a^{TT} = \frac{z_j^{TT}}{x^T} \tag{5}$$

Introducing the coefficients into the basic equation (Equ. 1), this equation becomes:

$$x^A = A^{AA}x^A + A^{AB}x^B + A^{AW}x^W + a^{AT}x^T + y^{AA} + y^{AB} + y^{AW} \tag{6}$$

Similar equations can be written for x^B and x^W. In the case of x^T, the equation becomes:

$$x^T = a^{TA}x^A + a^{TB}x^B + a^{TW}x^W + a^{TT}x^T + y^{TA} + y^{TB} + y^{TW} \tag{7}$$

A satisfies therefore the basic Input-Output relationship. This decomposition permits to evaluate the direct and indirect production in each region (A, B, W) or from the international transport sector (T) linked to any kind of final demand. Multipliers can be calculated with the Leontief inverse:

$$x = (I - A)^{-1} y, \tag{8}$$

where *I* is the identity matrix, $y = \begin{pmatrix} y^A \\ y^B \\ y^W \\ y^T \end{pmatrix} \,\&\, y^A = y^{AA} + y^{AB} + y^{AW} + y^{AT}$ (9)

, and the same definition apply to y^B, y^W and y^T.

SECTOR-AGGREGATED APPROACH & UNDERLYING-FLOWS DECOMPOSITION

The sector-aggregated approach is applied on the matrix obtained after the aggregation of emissions within each region (along rows and columns) of the matrix resulting from a classical resolution of a MRIO model. The classical resolution of the system answer to the following question: "What is the magnitude of the emissions induced domestically and in foreign countries by the final demand from country *d*?", by post-multiplying the Leontief inverse with the diagonalized vector of final demand from country *d*, and pre-multiplying the result by the diagonalised vector of emission factors (*f*).

For country d, the sector-aggregated matrix showing the total emissions (TE_d), induced by its final demand is:

$$TE_d = \hat{f}(I - A)^{-1}\hat{y}_d \tag{10}$$

$$\hat{f} = \hat{p}\hat{x}^{-1} \tag{11}$$

where the elements of p, p_d^j are the emissions of pollutant from sector j *(j=1 to n)* in country d (d=A, B, W) and from the international transport sector T.

2a

	A	B	W	T
A	A1 te^{AA}	te^{AB}	A2 te^{AW}	te^{AT}
B	te^{BA}	te^{BB}	te^{BW}	te^{BT}
W	A3 te^{WA}	te^{WB}	A4 te^{WW}	te^{WT}
T	te^{TA}	te^{TB}	te^{TW}	te^{TT}

2b

	A	B	W	T
A	te^{AA}	te^{AB}	te^{AW}	te^{AT}
B	te^{BA}	te^{BB}	te^{BW}	te^{BT}
W	te^{WA}	te^{WB}	te^{WW}	te^{WT}
T	te^{TA}	te^{TB}	te^{TW}	te^{TT}

A, B, W: 3 countries
T: Supranational transport sector
te^{dd}: Emissions induced in country (or international transport sector) d for the production of final goods from country (or international transport sector) d, d = A, B, W, T
te^{de}: Emissions induced in country d (or international transport sector) for the production of final goods from e (or international transport sector), e = A, B, W, T

Tables 2a & 2b Segmentations of the sector-aggregated matrix of total emissions (TE).

The sum of the cells corresponds to total emissions. Emissions in country s induced by the demand from country d for final goods of country e are shown by te_d^{se} in table 2a, with (s=A, B, W). In other words, rows are countries where emissions occur for the production of final goods bought from countries appearing in columns. This matrix can be split in four areas shown in table 2a. Assuming that country d is country A, domestic emissions can be split in two parts. Area 1 (A1) represents the emissions induced domestically by the domestic demand for domestic final goods, including their production and their domestic supply chains. Area 2 (A2) represents domestic emissions for the production of intermediary goods part of the international production chains of imported final goods from B, W and T. Foreign emissions can also be split in two parts. Area 3 (A3) represents the emissions in foreign countries B, W and by the supranational transport sector T due to the international supply chains of the domestic final goods from A, i.e. the foreign production of imported intermediary goods. Area 4 (A4) represents the foreign emissions (B, W and T) due to the supply chains for the imports of final goods by A.

The segmentation, shown in table 2b, can be used to compute the share of emissions emitted in the country from which final goods are imported. To get a result by country of origin, the computation should be performed column by column. The off-diagonal cells of the matrix represent emissions occurring along supply chains in a country different from the one providing the final goods. The diagonal cells represent emissions to produce final goods as well as the domestic part of their supply chains. For each country of origin, i.e. each column, dividing a diagonal cell by the sum of its column provides thus the share emissions emitted in the country of origin.

UNDERLYING-FLOWS DECOMPOSITION

The underlying-flows decomposition provides a description of the underlying causes of emissions from domestic economic activities by splitting them into eight underlying flows and by identifying the country being at the origin of these flows. This decomposition makes possible the identification of countries inducing the domestic emissions within a country trough their consumption, providing a reverse perspective to the sector-aggregated approach. This decomposition also provide insights on the structural causes of these emissions, to establishing typologies of countries with respect to main underlying causes, their role in international supply chains or the importance of international backward linkages of final goods.

We define underlying flows as the different type of economic flows contributing to the emissions occurring within a country *d*. Underlying flows are differentiated according to three criteria: (i) the location of the end-users, e.g. consumers, of final goods, (ii) the position of a good in a supply chain based on the nature of the flows in the Input-Output framework (intermediary or final goods), (iii) the nature of supply chains (domestic or international). The eight underlying flows are presented in the next paragraph from the viewpoint of a country (Germany) in a 3-country framework (Germany, France and USA). Numbers in bracket refer to figure 1, illustrating the eight underlying flows from the viewpoint of a "domestic" country. The left column corresponds to the domestic final demand, production and emissions in country *d* while the right column corresponds to foreign equivalents. The first row represents the users of final goods, i.e. final demand in the Input-Output framework (mainly households but also government and investment). The second row describes the production of final goods, i.e. goods sold to final demand only. The third row represents the supply chain of final goods, hence goods not sold to final users but to other producers, i.e. the production of intermediary goods in the Input-Output framework. Note that in the IO framework the same good can be either final or intermediary, according to its buyer. This classification distinguishes between domestic (2A, 4A) and international supply chains (2B, 4B, 5, 6).

The domestic emissions from economic activities within a country are induced to satisfy the consumption of final goods by its domestic population or by a foreign population. Both populations consume both domestic and foreign final goods. In the case of domestic consumption of domestic final goods, e.g. a German car in Germany, the production chain looks like the following. The latest production step is the domestic production of the final goods (1). The upstream supply chains (production of intermediary goods) of these final goods are either purely domestic (2A) or international, in which case the domestic part of these international chains, i.e. induced by intermediary imports linkages is described by (2B). In the second case of a foreign consumption of domestic final goods, e.g. a German car in France, the production chain is slightly different. The latest production step is again the domestic production of the exported final goods (3). The upstream supply chains (production of intermediary goods) of these exported final goods are either purely domestic (4A) or international, in which case the domestic part of these international chains, i.e. induced by intermediary imports linkages is described by (4B). In the third case, domestic emissions are induced for the domestic consumption of imported, i.e. foreign, final goods, e.g. a French car in Germany. The latest production step, i.e. the production of the imported good does not occur on the national territory but its upstream supply chains (intermediary goods) can be partially domestic, i.e. domestic intermediary goods are exported (5). In the last case, domestic emissions are induced for the foreign consumption of foreign final goods, e.g. a French car in the USA. Part of the upstream supply chain (production of intermediary goods) can be domestic, i.e. domestic intermediary goods are exported (6).

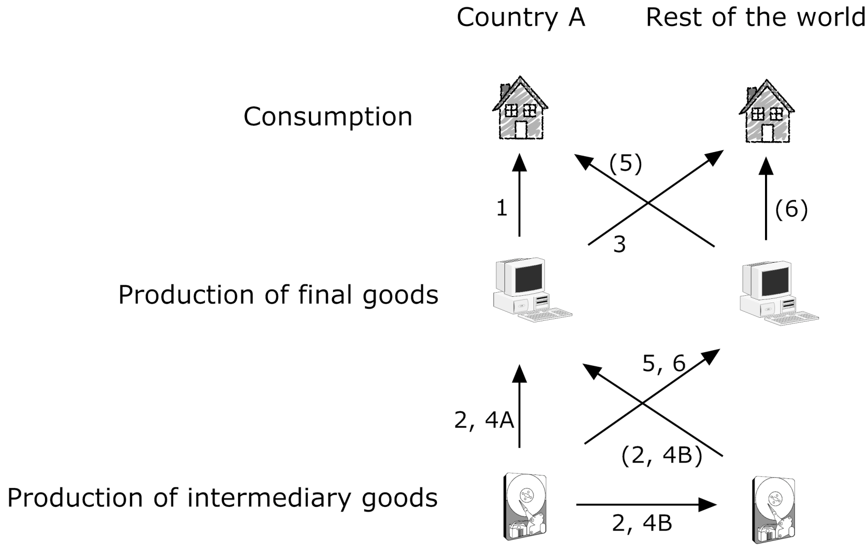

Figure 1 Underlying-flows decomposition with 2 countries and 2 goods. Numbers in brackets represent flows induced by the underlying-flows having the same number without brackets. Numbers in bracket are however not contributing to the emissions of the domestic country.

The analytical solutions of these eight underlying flows, based on the framework presented in section 1, are presented in table 3 for country *d*. The production of final goods corresponds to the various final demands expressed to country *d*, represented by the flows 1 and 3. Each block of the intermediate matrix corresponding to outputs of country *d*, i.e. row *d*, is then considered separately. For the domestic block, the distinction between domestic and international supply chains for the production of domestic final goods is achieved in two steps. Domestic linkages are considered by using only the national part of the technology matrix (A^{dd}) when computing the Leontief inverse (2A and 4A). International linkages (2B and 4B) are then computed by subtracting 2A from the Leontief matrix computed with the full technology matrix representing all linkages, i.e. $[(I-A)^{-1}]^{dd}$. The underlying flow 5, respectively 6, is the production of domestic intermediary goods that have to be produced to allow for the production of the foreign final goods to satisfy the domestic, respectively foreign, demands. Underlying flow 5, respectively 6, is computed by multiplying the part of the Leontief matrix corresponding to intermediary exports from *d* $[(I-A)^{-1}]^{de}$ with the domestic, respectively foreign, demand addressed to other countries. The emissions corresponding to underlying flows can be computed, in each case, by pre-multiplying them with the vector of domestic emissions (ef^{dd}). Underlying flows are grouped in table 3 according to final goods. The decomposition of domestic emissions per final user is simply computed by summing 1, 2 and 5 for domestic uses and adding 3, 4 and 6 separately for each country for foreign uses.

		Flow	Flow description	Analytical solution
Domestic final goods	Domestic consumption	1.	Production of final goods	y^{dd}
		2a.	Production of intermediary goods (domestic supply chains)	$[(I-A^{dd})^{-1}-I]y^{dd}$
		2b.	Production of intermediary goods (international supply chains)	$[H^{dd}-(I-A^{dd})^{-1}]y^{dd}$ $with\ H^{dd}=[(I-A)^{-1}]^{dd}$
	Foreign consumption	3.	Production of final goods	y^{de}
		4a.	Production of intermediary goods (domestic supply chains)	$[(I-A^{dd})^{-1}-I]y^{de}$
		4b.	Production of intermediary goods (international supply chains)	$[H^{dd}-(I-A^{dd})^{-1}]y^{de}$
Foreign final goods	Domestic consumption	5.	Production of intermediary goods (international supply chains)	$H^{de}y^{ed}$ $with\ H^{de}=[(I-A)^{-1}]^{de}$
	Foreign consumption	6.	Production of intermediary goods (international supply chains)	$H^{de}y^{eg}$ $with\ g\neq d$

Table 3 Underlying flows: descriptions and analytical solutions.

TREI-C MRIO MODEL : DATA SOURCES

The MRIO models developed during the TREI-C project is based on the GTAP database v.6., a global database calibrated on macro-economic and trade data from the World Bank and representing the world economy as flows of 57 goods and services between 87 regions, in millions U.S. dollars for 2001 (Dimaranan, 2006). Input-Output tables are adapted by the authors of the database to conform to the GTAP format. The GTAP database has been adapted to conform to the MRIO specifications. Main steps deal with (a) the estimation of trade flow matrices based on the assumption that each imported good is a weighted average of imports from all regions of origin, (b) the estimation of three supranational transport sectors by splitting the inputs of the existing transport sectors into domestic and international based on outputs, and using international trade margins as additional row, and (c) valuation to get an intermediary matrix at basic prices by splitting the price of imports into the price in the exporting country plus export taxes, international trade margins and import taxes, adding three rows to the flow matrix. Several grouping of countries are used to present results. They follow the classification of the United Nations (United Nations).

Emissions of CO2 used in this application are emissions available from GTAP, calculated with physical data from the GTAP energy database and IPCC emissions factors. A regional comparison with IEA publications (IEA, 2006) reveals differences ranging from 2 to 5 % on average, which is in the usual uncertainty range for CO2 emissions. Sector emissions can however be different from official emissions due to diverging sector definitions and due to the process of achieving global coherence at world scale.

CASE STUDIES: CARBON TARIFFS AND SHARING SCHEME

An overview of the results of the MRIO model is presented first. These results are in line with precedent studies by (Hertwich & Peters, 2009) using the same data set. The feasibility of EU carbon tariffs is firstly commented based on the share of embodied carbon emitted in the countries of origin of the final goods imported in Germany. An underlying flows decomposition of the Chinese emissions complements this answer and provide the basis for an analysis of the main contributors resulting in a proposal for an allocation scheme of de-carbonisation costs.

The magnitude and localization of CO_2 emissions generated by economic activities to satisfy the final demand of Germany, Western Europe (without Germany), Central Europe, China, the USA and the rest of the world (ROW) are presented in Table 4. All emissions from economic activities occurring along the supply chains of consumed products and services are included but not direct emissions from households. Column 5 shows, for example, that the CO_2 emissions generated by the US final demand are occurring for 86 % in the USA: less that 15 % is emitted in foreign regions, mainly on the American continent (3 %). These emissions, representing 26 % of all CO2 emissions, are very close to the amount of emissions on the US territory (24 % of emissions) in 2001.

	Germany	WE	CE	China	USA	ROW		CO2 emissions [Kt]	World shares
Germany	62.29%	2.99%	1.41%	0.25%	0.33%	0.40%		593'489	2.95%
Western Europe (less Germany) (WE)	8.72%	66.20%	3.11%	0.71%	1.31%	1.49%		1'890'055	9.41%
Central Europe (CE)	4.03%	2.59%	79.29%	0.21%	0.35%	0.51%		803'690	4.00%
Eastern Europe & Central Asia	4.64%	4.86%	6.61%	1.83%	1.03%	18.92%		1'876'931	9.34%
Africa	1.88%	2.62%	0.73%	0.48%	0.72%	6.62%		682'055	3.40%
Arabian Peninsula/Mashriq/Israel	1.54%	2.08%	0.94%	1.14%	0.98%	10.57%		1'027'478	5.11%
South Asia	0.60%	0.78%	0.29%	0.34%	0.32%	10.96%		961'032	4.78%
China	3.96%	3.61%	1.34%	88.72%	2.51%	2.79%		2'845'232	14.16%
Rest of Asia	2.75%	3.01%	0.99%	2.86%	1.49%	24.42%		2'280'262	11.35%
USA	3.54%	3.94%	1.03%	1.11%	86.08%	2.47%		4'827'757	24.03%
Americas (less USA)	1.60%	2.10%	0.53%	0.52%	3.14%	15.15%		1'500'823	7.47%
International transport	4.44%	5.22%	3.72%	1.83%	1.73%	5.69%		799'000	3.98%
CO2 emissions induced by consumption [Kt]	726'386	2'403'730	815'034	2'657'179	5'186'572	8'298'901		20'087'802	
World shares	3.62%	11.97%	4.06%	13.23%	25.82%	41.31%			

Table 4 Worldwide distribution of CO_2 emissions [Kt] induced by the domestic final demand of regions in columns. Grey cells indicate largest values in each column.

We show that domestic emissions are dominant in each of the countries and regions but proportions differ however largely. Around a third of emissions induced for the production of goods consumed in Germany and Western Europe are emitted in other regions. Both countries have a similar geographic distribution of emissions, the largest foreign emissions coming from neighboring regions, as expected from trade patterns. USA and China representing more than 3 % each. China has a similar profile than the USA with less than 15 % of emissions induced by consumption occurring elsewhere. These results for carbon contrasts strongly with the distribution of impacts on human health from fine particulates induced by consumption which are even further away than carbon from what is expected when looking at economic data (Friot, Shaked *et al.*, 2009).

The sector-aggregated matrix induced by the consumption of German households is shown in Table 5. Three quarters (76 %) of the carbon emissions induced by the final goods consumed in Germany are for final goods of German origin. Their production chains (A3) are however largely international since 29 % of the induced emissions happen outside Germany. The embodied carbon content, i.e. the carbon emitted along the supply chain, of the final goods from other origins is between 11 % and 38 % emitted in another region than the country of origin. The regions presented in Table 5 are large. (Hertwich *et al.*, 2009) have shown that for small open economies with a low fossil-fuel energy basis like Switzerland, the foreign share of emissions induced by consumption can be as large as 64 %.

	GE*	WE**	CE**	EA**	AS**	AM**	IS**	CO_2 emissions in each region [Kt]	World shares
GE	291'335	1'212	443	37	99	47	211	293'383	54.73%
WE	27'611	24'480	948	135	336	184	722	54'416	10.15%
CE	10'950	1'128	13'697	68	90	50	214	26'196	4.89%
EA	27'382	4'388	2'084	9'252	1'337	392	1'059	45'893	8.56%
AS	21'886	3'202	901	299	22'125	523	884	49'821	9.29%
AM	16'416	2'392	420	116	690	12'044	619	32'697	6.10%
IS	13'777	2'559	1'174	194	823	266	14'855	33'649	6.28%
CO_2 emissions due to final goods per region of origin [Kt]	409'357	39'361	19'667	10'101	25'500	13'505	18'564	536'055	
World shares	76.36%	7.34%	3.67%	1.88%	4.76%	2.52%	3.46%		
Share of domestic emissions	71.17%	62.19%	69.64%	91.60%	86.76%	89.18%	NA		

GE: Germany
WE: Western Europe (less Germany)
CE: Central Europe
EA: Eastern Europe, Central & West Asia, Africa
AS: China, South Asia & Rest of Asia
AM: USA & Americas
IS: International transport

*Table 5 Sector-aggregated matrix showing the distribution of CO_2 emissions [Kt] induced worldwide by German households consumption. * are domestic final goods. ** are imported final goods per region of origin.*

This simple aggregated view shows that while a dominant share of the average embodied carbon is emitted in the country of origin of the final goods, a substantial share of emissions can however occur in other countries due to international production chains. A carbon import tariff based on the country of origin of imported goods can thus be misleading in the case where the country of origin has a different carbon profile than countries along its supply chains. This could be case, for example, for EU imports of high-tech products from Switzerland, having an hydraulic-based electricity production, which are mainly produced in China, having a fossil fuel-based electricity production (IEA, 2006).

The underlying flows decomposition for China is presented in Table 6. Chinese emissions from economic activities are largely induced to satisfy the Chinese domestic consumption (70 %) (1, 2A, 2B, 5). The bulk of these emissions are due to the purely domestic supply chains (2A) (77 %) of Chinese final goods. The share of emissions due to their international production chains (2B, 5) is very small, around half a percent of total Chinese emissions.

Flow	Underlying flows		CO_2 emissions [Kt]	Shares
1	Final goods	**Locally consumed in China**	457'224	16.07%
2a	Intermediary goods	Domestic upstream chain	1'534'758	53.94%
2b	Intermediary goods	International upstream chain	9'107	0.32%
3	Final goods	**Exported to USA**	11'296	0.40%
4a	Intermediary goods	Domestic upstream chain	124'088	4.36%
4b	Intermediary goods	International upstream chain	868	0.03%
3	Final goods	**Exported to Western & Central Europe and Germany**	8'547	0.30%
4a	Intermediary goods	Domestic upstream chain	72'480	2.55%
4b	Intermediary goods	International upstream chain	502	0.02%
3	Final goods	**Exported to other countries**	13'715	0.48%
4a	Intermediary goods	Domestic upstream chain	124'044	4.36%
4b	Intermediary goods	International upstream chain	844	0.03%
5	Intermediary goods	**For domestic demand of foreign goods**	5'275	0.19%
6	Intermediary goods	**For demand of foreign goods by**		
		USA	143'725	5.05%
		Western & Central Europe and Germany	130'354	4.58%
		Other regions	208'405	7.32%
	Total		2'845'232	

Table 6 Underlying flows decomposition of Chinese CO_2 emissions.

Emissions for foreign consumers are mainly due to triangular trade (6) (17 %), i.e. the production of intermediary goods for the provision of final goods by a third party, e.g. a Japanese TV sold on the US market. Emissions from the production of Chinese final goods (3), including their supply chains (4A, 4B), sold to foreign consumers are lower (12 %). This situation reflects the position of China in world production chains as a world factory (Hongling Zhang, 2006), hence producing mainly intermediary goods. Emissions from the production chains of these Chinese final goods are, as those sold to domestic consumers, mainly due to domestic production chains rather than international ones. From an aggregated view, the goods consumed in the rest of the world, e.g. by households, are thus mainly responsible of emissions in China but not much in the rest of the world. The US consumption is the largest foreign driver of Chinese CO_2 emissions accounting for 10 % of all emissions from production activities. This is around one third of all emissions induced for foreign consumers. These emissions induced for foreign consumption are equivalent to the third of the emissions in Western Europe including Germany.

Emissions linked to triangular trade correspond to the emissions that could not be captured by a tariff scheme focusing on the country of origin only. From a EU viewpoint (Western Europe, Germany & Central Europe), close to 5 % of the emissions in China are due to triangular trade, i.e. occurring for producing intermediary goods, which are exported towards a non-EU country where they are used for producing final goods imported in the EU. This is larger than the emissions that can be captured. This result indicates the potential un-ability of such a tariff scheme to adequately capture a large share of emissions induced by the EU in the rest of the world.

A sharing scheme of de-carbonisation costs in China resulting from the application of the "underlying flows decomposition" to this MRIO model is presented in Figure 2a. Several schemes could have been designed. To adopt a scheme in accordance with the Kyoto protocol, we apply a sharing scheme including only countries of the Annex II of the Kyoto protocol, which are the developed countries that agreed to pay some of the costs of developing countries, assuming that this fact would still be valid in the future. Among the twelve largest contributors, only two countries are not among these members and thus not included in Figure 2: Korea inducing around 1 % of Chinese carbon emissions and countries of the Middle-East inducing around half a percent of these emissions. The potential interest of such a scheme is confirmed by the large contribution of the Annex II countries as a group, which amounts for 78 % of Chinese emissions induced by foreign final demands. The countries inducing the most emissions are the USA, Japan, Germany, the United Kingdom, France and Canada. Assuming the application of the here-proposed allocation scheme, these six countries would assume more than 80 % of the de-carbonisation costs supported by foreign economies in China. The comparison of this scheme with a scheme based on the emissions reported to the UNFCCC in 2001, presented in Figure 2b, show that the distributions are overall similar in both cases with large differences for some countries. Under the hypothesis that the costs of de-carbonisation of China would be split among countries of the Annex II based on their direct emissions, the share of the USA would be larger (+ 6 %), as would be the share of the Canada (+ 2 %) and Australia (+ 1.5 %). The share of Japan would be strongly reduced (- 10 %) while the contribution of the EU countries would be almost similar except for Italy (+ 1 %).

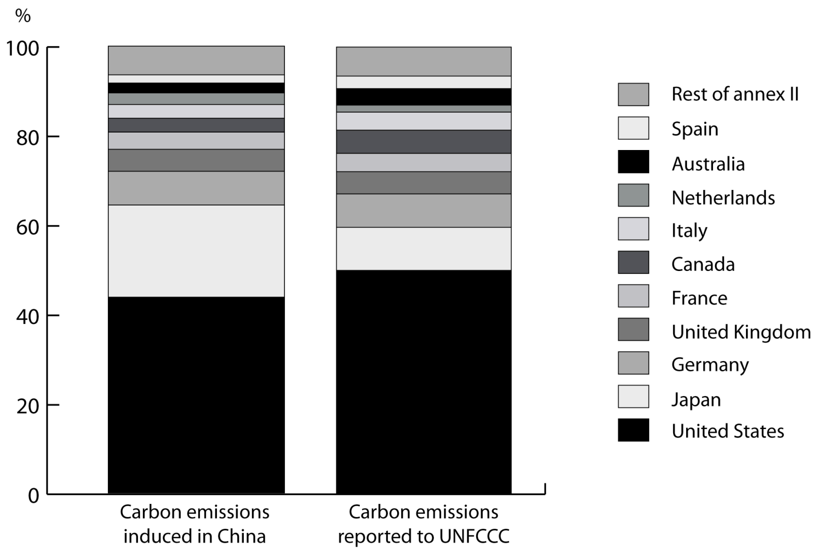

Figure 2a & 2b Sharing scheme of de-carbonisation costs in China: a) based on the distribution of Chinese emissions induced by foreign countries, b) based on the carbon emissions reported to UNFCCC in 2001. Only countries of the annex II of the Kyoto protocol are considered.

DISCUSSION & CONCLUSION

The underlying-flows decomposition provides a new structural analysis with a specific focus on the international dimension. This analysis complements existing analytical capacities based on Input-Output models like the ones presented by (Peters *et al.*, 2006), (Wier, 1998) and (Fernandez-Vazquez *et al.*, 2008).

We have applied this decomposition to show that, for final goods, carbon tariffs based on the country of origin would not be very representative of their embodied carbon. We have applied here a simple definition of the country of origin, which is enough for our purpose. This definition does not however match the complexity of the EU definition, which defines the country of origin based on rules of origin. Origin is the "economic" nationality of goods in international trade (Commission of the European Communities, 1993; European Comission). The EU defines this nationality based on the substantial transformation method, stating that « a good originates from the last country where it emerged from a given process with a distinctive name, character or use » (International Trade Centre UNCTAD/ WTO, 2000). This criterion is defined only in broad terms and further tests, like technical tests, domestic content test or a change in tariff classification are used to define it. In the case of an application of carbon tariffs, more complex solutions should therefore be applied, like computing the embodied carbon content of any of the imported goods.

Multi-Regional Input-Output models are the only models able to present a life cycle perspective on a global scale. While these models are in need for improvement (Tukker *et al.*, 2009; Wiedmann *et al.*, 2007) and the used databases quite outdated, existing models can be used to deliver first analytical tools and answers to questions related to globalization, like presented here or, for example, by Peters (Peters & Hertwich, 2007). They are however not detailed enough for computing the embodied carbon content of any of the imported goods and will need to be complemented by other approaches like Process Life Cycle Assessment (Friot, Blanc *et al.*, 2009).

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Chapitre 5 : Conclusion

Cette thèse sur l'intégration des contraintes liées à la mondialisation, des échanges et des responsabilités, au sein des méthodes de comptabilité environnementale nous a permis d'atteindre plusieurs objectifs : le développement d'un cadre d'analyse permettant l'évaluation des forces et faiblesses des EAMs existantes ainsi que de leur potentiel d'intégration des problématiques liées à la mondialisation, l'analyse des principales EAMs à l'aide de ce cadre d'analyse, l'extension d'un modèle existant afin de faire un pas en direction de l'intégration des contraintes liées à la mondialisation, et enfin l'application de ce modèle pour étudier trois problèmes clés liés à la mondialisation : les impacts environnementaux sur la santé humaine dans les pays en voie de développement, les tarifs douaniers aux frontières de l'Europe liés au contenu en carbone des produits importés et le rôle des pays développés dans les émissions de carbone chinoises. Les conclusions principales de cette thèse sont brièvement rappelées et mises en perspective. Certaines des pistes de recherche identifiées dans cette thèse, et qui nous semblent personnellement les plus intéressantes, sont ensuite discutées en guise de conclusion.

Le cadre d'analyse, permettant d'évaluer la réponse apportée par les EAMs aux attentes sociétales qui leur sont adressées ainsi que la manière dont elles font face aux défis de la mondialisation, est le premier cadre d'analyse développé spécifiquement à cet effet. Il complète les évaluations existantes par une vision méthodologique et systématique. L'application de ce cadre d'analyse aux principales EAMs existantes a permis d'en identifier les forces et faiblesses de manière structurée. Une conclusion importante de cette analyse est que pour le temps présent, les modèles entrées-sorties constituent le cœur de l'approche préconisée pour une évaluation pertinente des impacts correspondant au mode de consommation actuel marqué par la mondialisation. Leurs limites étant cependant actuellement importantes, de nombreux développements méthodologiques et de données sont encore nécessaires afin d'obtenir des résultats robustes. Une deuxième conclusion est qu'une attention particulière devra être portée au développement des indicateurs afin de rendre compte d'une vision vraiment globale. Cette vision considère autant les dégradations environnementales localement critiques le long des chaînes de production que les dégradations qui sont critiques au niveau mondial. L'adaptation de ces indicateurs est un défi scientifique et politique puisqu'elle implique un changement de perspective, allant d'une vision classique centrée sur l'Etat-Nation à une vision réellement mondiale.

Le modèle intégré « Economie-Environnement-Impacts » développé dans cette thèse et basé sur les orientations issues de l'analyse précédente, répond à certains manques actuels des EAMs. Il combine avec succès un modèle économique mondial de type MRIO, un modèle multi-continental atmosphérique de transport de polluants et d'exposition humaine (IMPACT World) et des facteurs de dommages sur la santé humaine provenant du modèle IMPACT02+. Ce modèle nous a permis d'analyser les impacts sur la santé humaine résultant des particules fines induites par les modes de consommation, production et d'échanges actuels et de générer les premiers résultats quantifiés selon une vision cycle de vie globale à ce sujet.

Nous avons trouvé que les impacts sur la santé humaine induits par la consommation de l'Allemagne et des Etats-Unis ont principalement lieu à l'extérieur de ces pays, principalement en Chine (plus de 40 % des impacts induits, par exemple, par la consommation allemande ont lieu en Asie), malgré le fait qu'une faible part seulement des biens consommés par ces deux pays soit d'origine étrangère. Ce résultat montre l'intérêt de faire évoluer les EAMs existantes vers une évaluation à l'échelle mondiale comme nous l'avons fait dans ce travail. Il montre également l'importance de développer des modèles régionaux ou nationaux hors d'Europe et des Etats-Unis afin d'améliorer la précision des résultats. Du point de vue de l'application actuelle des EAMs, ce résultat montre que les pratiques et recommandations en cours en Europe, en terme d'étiquetage environnemental par exemple, sont potentiellement inadéquates dans le cas où elles ne prennent pas en compte les spécificités locales des pays extra-européens desquels proviennent les biens importés ainsi que dans lesquels se situent les chaînes de production. La prise en compte de ces spécificités est possible actuellement moyennant des développements méthodologiques et de données ainsi que la mise en place de directives méthodologiques d'application puisque les méthodes de comptabilité environnementales sont, et resteront, basées sur des hypothèses qui doivent être acceptées et transparentes pour les utilisateurs.

Nous avons également identifié que la délocalisation de la production dans les nouveaux pays manufacturiers tels que la Chine, ayant des intensités d'émission par dollar de production bien supérieures à la moyenne européenne, est le facteur d'explication principal des impacts sur la santé humaine liés à la production des biens consommés par les pays européens. Enfin, nous avons également constaté une exportation « implicite » des activités de production les plus dommageables en terme de santé humaine vers les pays en voie de développement. Cette exportation est « implicite » car elle résulte des efforts très significatifs de diminution des émissions polluantes au niveau européen. Elle ne correspond ainsi pas une exportation « explicite » des activités les plus polluantes. Ces résultats montrent les limites des politiques de l'environnement purement nationales dans un monde caractérisé par des chaînes de production-consommation mondiales et l'intérêt d'une réflexion, de modèles et de politiques, à un niveau régional, voire mondial. La démarche conjointe entreprise dans le cadre de la commission économique pour l'Europe (CEE-ONU ou « UNECE » en anglais) débouchant sur divers protocoles et conventions sur les flux transfrontaliers de polluants, par exemple, la Convention sur la pollution atmosphérique transfrontière à longue distance, ou le Protocole d'Aarhus relatif aux métaux lourds, et sur des répertoires d'émissions, semble ainsi particulièrement pertinente et gagnerait à être étendue à plus large échelle. Ces résultats confirment également l'intérêt, si cela est encore nécessaire, de la mise sur pied d'un organe des Nations-Unies (ou une organisation apparentée comparable à l'Organisation Mondiale du Commerce) spécifique aux questions environnementales.

L'application des méthodes d'analyse des modèles MRIO développées dans cette thèse a permis de montrer qu'un tarif douanier approximant le contenu attaché en carbone des importations aux frontières de l'Europe en se basant sur les pays d'origine n'est pas une solution qui semble adéquate. Un tel schéma ne permet pas de quantifier adéquatement le contenu attaché en carbone des biens importés car il ne tient pas compte des chaînes de production mondiales. Une partie des émissions de carbone induite par la consommation européenne échappe à ce type de tarif, particulièrement dans les pays ateliers comme la Chine. Nous estimons qu'il faut quantifier le contenu attaché en carbone de chacun des produits importés. Cette quantification semble difficile à réaliser actuellement sans un effort financier important pour développer de nouvelles bases de données, évaluer les produits dans le détail et mettre sur pied un système flexible capable de permettre l'évaluation des nouvelles importations très rapidement. Ce dernier aspect nous semble hors de portée des EAMs actuellement. Les analyses développées ont également été appliquées afin de déterminer une clé de partage des coûts de dé-carbonisation de la Chine se basant sur les postulats que ce partage pourrait être établi en fonction du rôle des pays étrangers dans les émissions chinoises et que l'allocation se baserait sur une perspective de cycle de vie. En partant de l'hypothèse que seuls les pays de l'annexe II du protocole de Kyoto participeraient financièrement, environ 80 % des coûts seraient supportés par les contributeurs principaux que sont les États-Unis, l'Allemagne, le Royaume-Uni, la France et le Canada. Les clés de partage de la prise en charges des coûts de dé-carbonisation des pays en voie de développement sont actuellement discutées au niveau de l'EU, en préparation à la prochaine Conférence sur le Climat à Copenhague. Cette proposition, basée sur une notion de causalité, n'a cependant pas été envisagée au niveau politique pour l'instant à notre connaissance.

Cette thèse s'inscrit dans une période que nous avons qualifiée « de convergence ». Les projets se multiplient et certaines innovations méthodologiques deviennent rapidement des standards incontournables, comme l'application des modèles MRIO étendus, par exemple. Alors qu'il y a quelques années, les conférences de l'IIOA (International Input-Output Association) étaient centrées sur des questions économiques, les questions environnementales sont devenues une partie essentielle de celles-ci depuis la conférence de l'association en 2007 à Istanbul. Cette orientation ne cesse de se renforcer depuis lors, le nombre de sessions consacrées aux modèles MRIO étendus étant également en constante augmentation.

Cette convergence débouche également sur un développement accru des données environnementales concernant les pays extra-européens. La qualité des données utilisées dans cette thèse ne reflète ainsi déjà plus l'état de l'art en la matière. Certains groupes de recherche ont fait du carbone leur fer de lance et ont contribués à l'amélioration des versions ultérieures de la base de données utilisée dans cette thèse (Hertwich, 2009). De nouveaux jeux de données ont également été développés pour l'Asie depuis l'élaboration de l'inventaire des particules fines, dans le cadre du projet GAINS-Asia de IIASA (IIASA, 2009). La comparaison avec cet inventaire, considéré comme une référence, montre une large sous-estimation par notre inventaire pour les régions asiatiques, ce qui va dans un sens du renforcement de la tendance des résultats obtenus mais montre également les limites du développement de ce type de modèle hors d'un cadre de collaboration impliquant des spécialistes de chaque domaine, dont les générateurs d'inventaire. C'est afin de pallier à ce genre de limites que l'Union Européenne a décidé de financer le projet EXIOPOL (FEEM, 2008), rassemblant plus de trente partenaires, afin de développer des bases de données entrées-sorties et des extensions environnementales nécessaires au niveau mondial, et de rendre ces données, ainsi que leurs méthodologies, publiques et transparentes.

Cette convergence pousse également à la comparaison des EAMs avec les modèles disponibles dans d'autres domaines, comme en économie ou en sciences de l'ingénieur. Les capacités des EAMs semblent bien limitées de ce point de vue. Principalement appliquées pour établir un état des lieux valable à un instant donné, très peu d'entre elles intègrent une approche dynamique. L'utilisation de scénarios dans des buts de prospective est également encore limitée et complexe. Les modèles MRIO étendus ne font pas exception. Rendre ces modèles dynamiques passe par l'endogénéisation de la demande des ménages et de la demande d'investissement. Cette endogénéisation peut être réalisée en intégrant des estimations économétriques de ces demandes et en fermant le modèle par l'établissement d'un lien entre consommation, investissement et revenu. La modélisation des demandes d'investissement par les secteurs d'activités est la plus difficile à résoudre puisque les données ne sont disponibles que pour un nombre réduit de pays. Le lien entre revenus, dépenses et investissements est ainsi rarement réalisé avec des modèles détaillés. Ce lien est pourtant souhaitable afin de pouvoir estimer les conséquences graduelles des différentes politiques ou décisions prises.

Cette thèse s'est concentrée sur l'intégration des contraintes liées à la mondialisation dans les méthodes de comptabilité environnementales, particulièrement dans les modèles entrées-sorties étendus mondiaux. Parmi les directions de recherche identifiées au cours de cette thèse, la première est évidente. Elle tient à l'extension de ce type de modèle afin d'intégrer les trois dimensions (économie, social, environnement) du développement durable de manière cohérente. Les modèles MRIO considèrent déjà les aspects économiques et environnementaux. Ils peuvent, par exemple, être étendus à la dimension sociale par l'intégration de matrices de comptabilité sociale (SAM) (social accounting matrix, en anglais) (Pyatt & Round, 1985) permettant de considérer la distribution des revenus par type de ménage. D'autres extensions sociales sont cependant encore à développer. La démarche inverse semble également souhaitable, c'est-à-dire que les leçons de cette intégration économie-environnement-impacts servent à l'extension de modèles économiques plus élaborés que ceux que nous avons utilisés.

D'autres directions de recherche, plus novatrices, nous semblent également souhaitables. La première tient au partage des responsabilités quant aux impacts environnementaux. Différents auteurs, dont Lenzen (2007) ont étudié comment allouer la responsabilité entre producteurs et consommateurs le long d'une chaîne de production-consommation. Un troisième type d'acteurs manque cependant dans les modèles actuels: les détenteurs des moyens de productions capital (actionnaires) et travail (salariés). Ces acteurs ont un pouvoir de décision important au sein des activités de production et l'identification ainsi que la quantification de leurs responsabilités permettrait de générer un regard complémentaire sur les émissions et impacts actuels en identifiant de nouvelles voies d'action potentielles. Il est possible d'explorer une telle démarche par l'extension des modèles entrées-sorties développés dans cette thèse. La composante internationale en est essentielle compte-tenu de la distribution géographique des propriétaires des grands groupes industriels aujourd'hui. Cette direction de recherche s'inscrit dans les extensions envisagées par le développeur des modèles entrées-sorties, Leontief (1936) concernant les flux financiers. Elle demande l'extension des modèles entrées-sorties afin de bâtir une SAM (social accounting matrix, en anglais) détaillée, en se basant sur les comptes nationaux et des données financières d'entreprises. Longtemps inaccessible pour des raisons de manque de données, cette recherche devient actuellement possible.

La seconde direction de recherche novatrice est le développement de méthodes d'évaluation des impacts là où elles font le plus cruellement défaut : au niveau des entreprises. Une réflexion semble souhaitable sur la réalisation d'évaluations multi-échelles intégrées (entreprise - unités fonctionnelles – site - produit), permettant de connecter ces niveaux de manière explicite afin d'augmenter la cohérence entre les niveaux et de réduire les efforts de collecte de données et de modélisation. Les défis sont ici dans la transposition d'un modèle mathématique dans un contexte d'entreprise et l'identification, ainsi que la modélisation, de clés d'allocations pertinentes pour le passage entre les échelles, clés spécifiques aux différents biens et fonctions, ainsi qu'aux différents objectifs.

Chapitre 6: Références (de l'introduction et de la conclusion)

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COMPTABILITE ENVIRONNEMENTALE ET MONDIALISATION

QUELS DEFIS ? QUELS MODELES POUR Y REPONDRE ?
APPLICATION D'UN MODELE ECONOMIE-ENVIRONNEMENT-IMPACTS A L'EVALUATION DES IMPACTS ENVIRONNEMENTAUX EN CHINE INDUITS PAR L'EUROPE, ET AUX TAXES CARBONE AUX FRONTIERES DE L'UE

Résumé

Cette thèse traite de l'intégration des contraintes liées à la mondialisation dans les méthodes de comptabilité environnementales. Nous proposons tout d'abord une analyse de la capacité des principales méthodes actuelles à répondre aux attentes sociétales et à relever les défis liés à la mondialisation. Nous développons à cette fin le premier cadre analytique spécifique à ces méthodes. Nous développons ensuite un modèle intégrant certaines des contraintes liées à la mondialisation. Ce modèle combine un modèle entrées-sorties mondial, décrivant les activités de production, de consommation et de commerce international ainsi que les émissions qui en résultent, avec un modèle mondial de transport de polluants intégrant l'exposition humaine, et un modèle d'impact environnemental. Nous appliquons ce modèle pour établir la première quantification des impacts environnementaux sur la santé humaine liés aux émissions de particules fines ($PM_{2.5}$) induits par la consommation des pays de l'OCDE dans le reste du monde selon une perspective cycle de vie. Nous appliquons ensuite le modèle entrées-sorties pour analyser le potentiel d'une taxe carbone aux frontières de l'UE. Nous proposons enfin un nouveau type d'analyse structurelle que nous appliquons aux émissions de carbone chinoises afin de déterminer quels sont les pays qui induisent ces émissions de par leur consommation, c'est à dire pour la production des biens et services exportés en incluant leurs chaines de production. Cette analyse est utilisée pour déterminer un potentiel schéma de partage international des coûts de dé-carbonisation de la Chine, tel qu'évoqué durant les préparatifs de la conférence sur le climat de Copenhague.

Mots clés : analyse entrées-sorties, cycle de vie, santé humaine, impacts environnementaux, réchauffement climatique, mondialisation

ENVIRONMENTAL ACCOUNTING AND GLOBALISATION

WHICH MODELS TO TACKLE NEW CHALLENGES?
APPLYING ECONOMICS-ENVIRONMENT-IMPACTS MODELS TO EVALUATE ENVIRONMENTAL IMPACTS INDUCED BY EUROPE IN CHINA, AND EU CARBON TARIFS

Abstract

Environmental accounting methods are facing challenges from globalization. Firstly, we analyze how the main methods are currently answering to societal expectations and how they deal with these challenges. We develop an innovative specific analytical framework to perform this evaluation. Then, we propose a global model integrating several constraints resulting from these challenges. This model combines *i)* a multi-regional input-output model, describing goods and services production, consumption and trade as well as induced emissions, *ii)* a pollutant transport model including human exposure and *iii)* an environmental impact model. We apply this model to provide the first quantification of the environmental health impacts from particulate matter ($PM_{2.5}$) induced by the consumption of OECD economies in the rest of the world, based on a life cycle perspective. We then apply the global input-output model to analyze the potential interest of EU carbon tariffs. We finally propose a new type of structural analysis and apply it to Chinese carbon emissions. The countries inducing these emissions through their consumption, i.e. for the production of exported goods and services including supply chains, are identified. Based on this analysis, we propose an international sharing scheme of the de-carbonization costs of China, as discussed during the preparation of the Copenhagen Climate Conference.

Key words: Input-Output Analysis, life cycle, human health, environmental impacts, climate change, globalisation

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